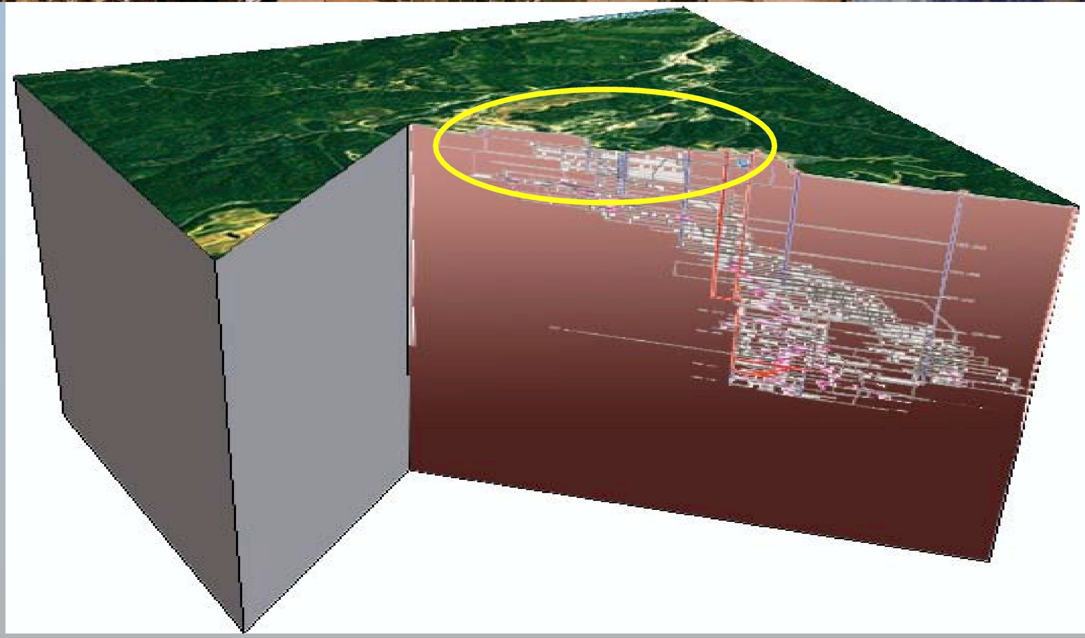
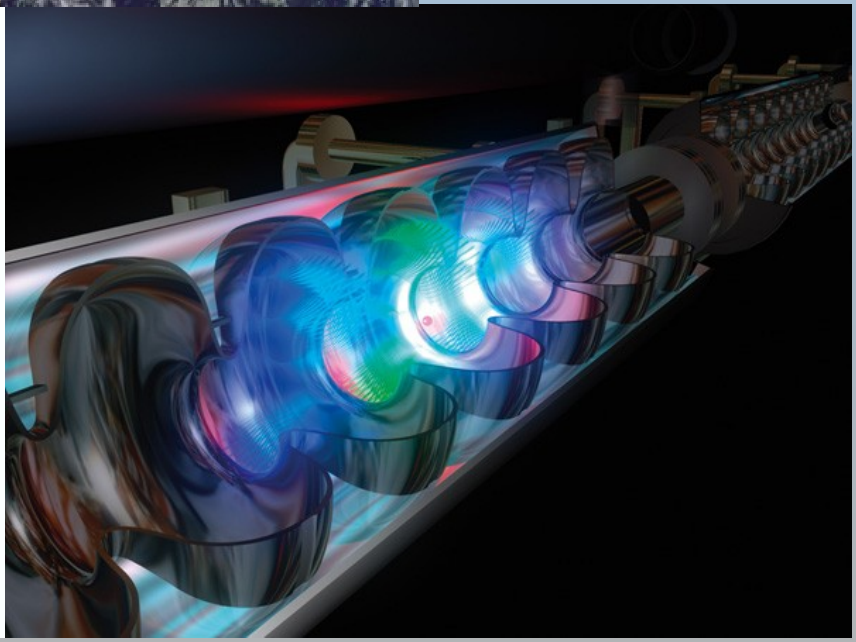
Solving The Dark Matter Problem



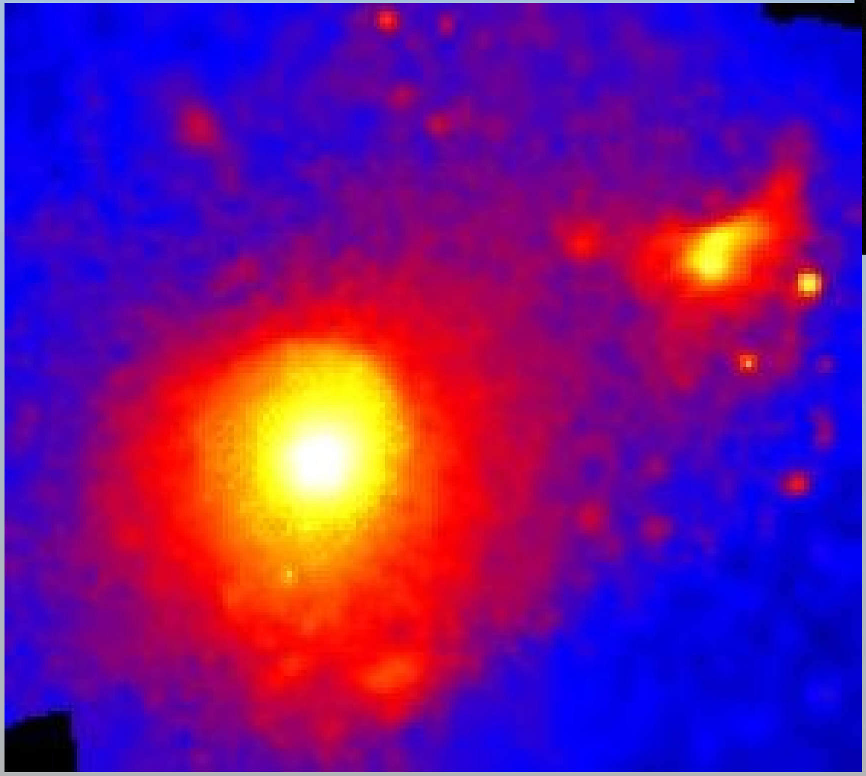


What Is The Dark Matter Problem?

First evidence: cluster mass/light observed by Zwicky (1930s)

Luminous matter did not explain velocities of cluster members by a factor of more that 10

Virgo Cluster



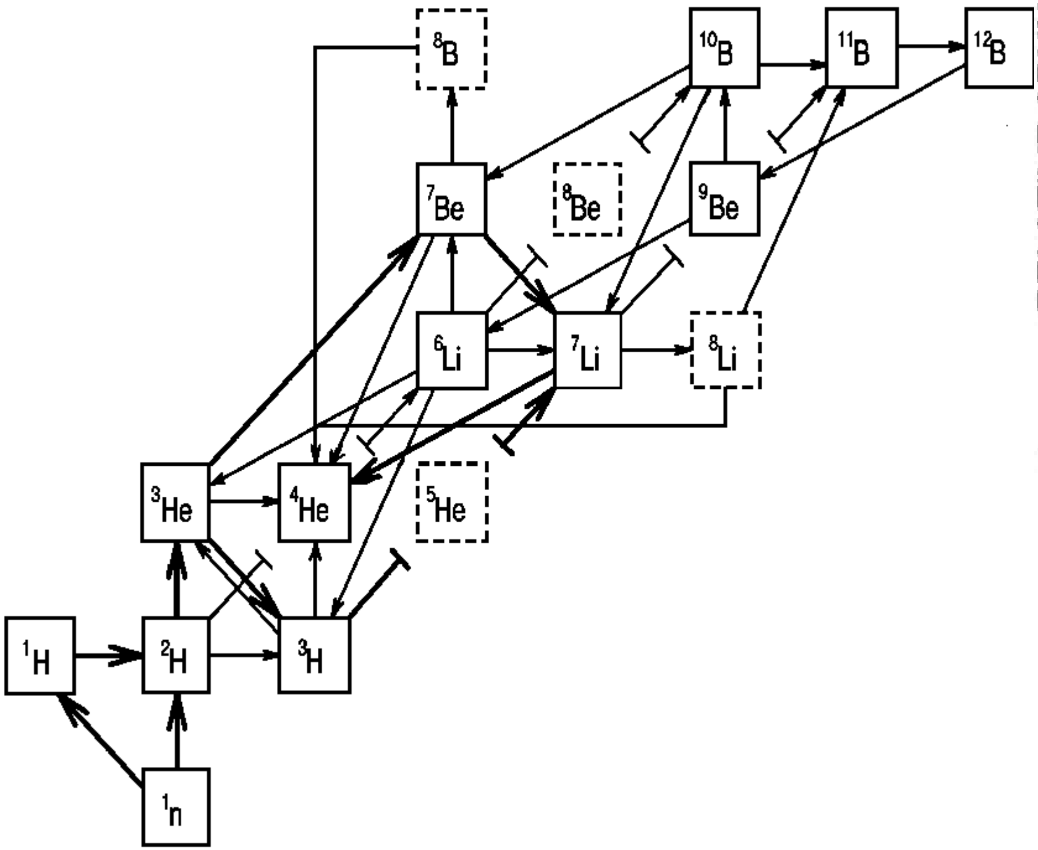
Most cluster baryons are in hot gas (observed in X-rays): brightness gives gas mass, temperature gives total mass

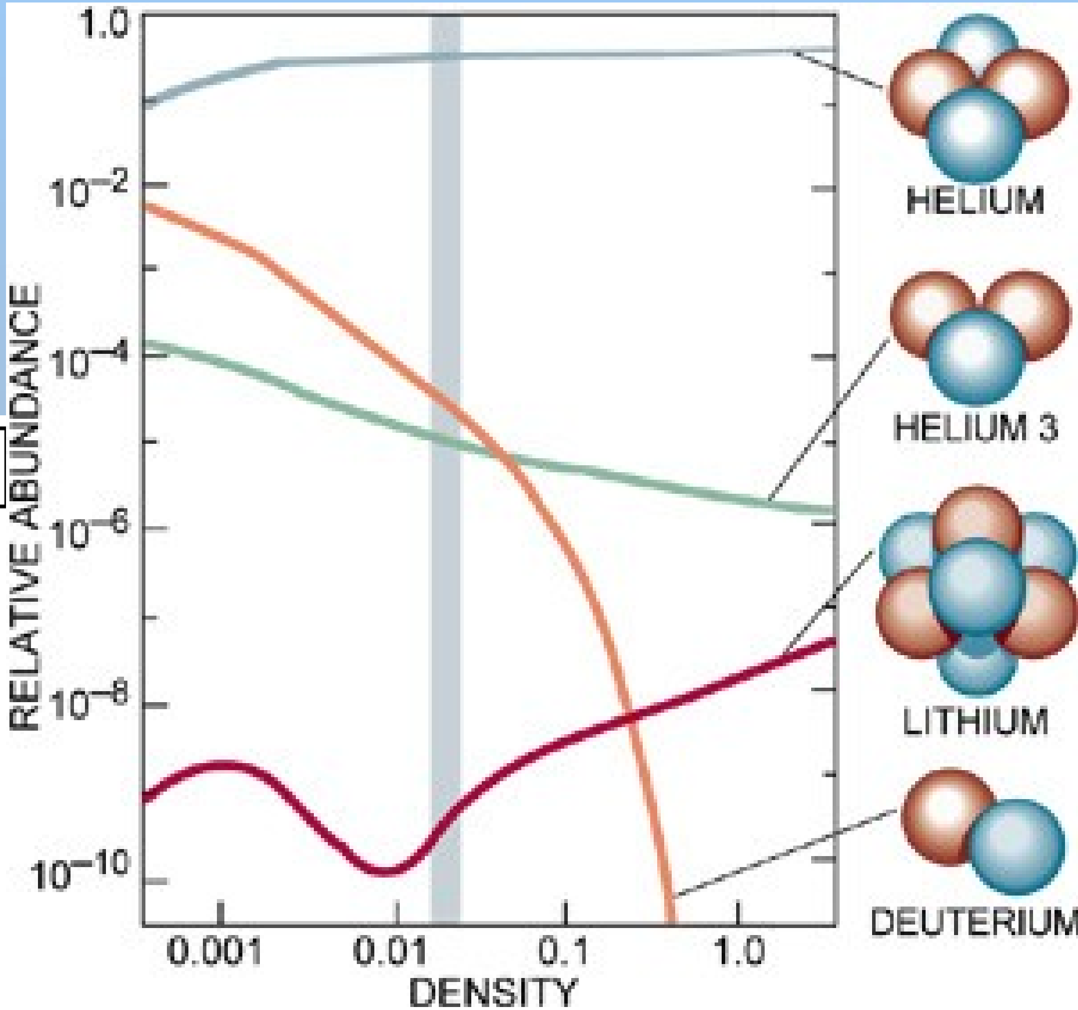
Still short by a factor of ~5!

Big Bang Nucleosynthesis

Synthesis of light elements in hot big bang (T~MeV) depends on baryon / photon ratio
Production of deuterium is most sensitive

Elements beyond lithium very rare



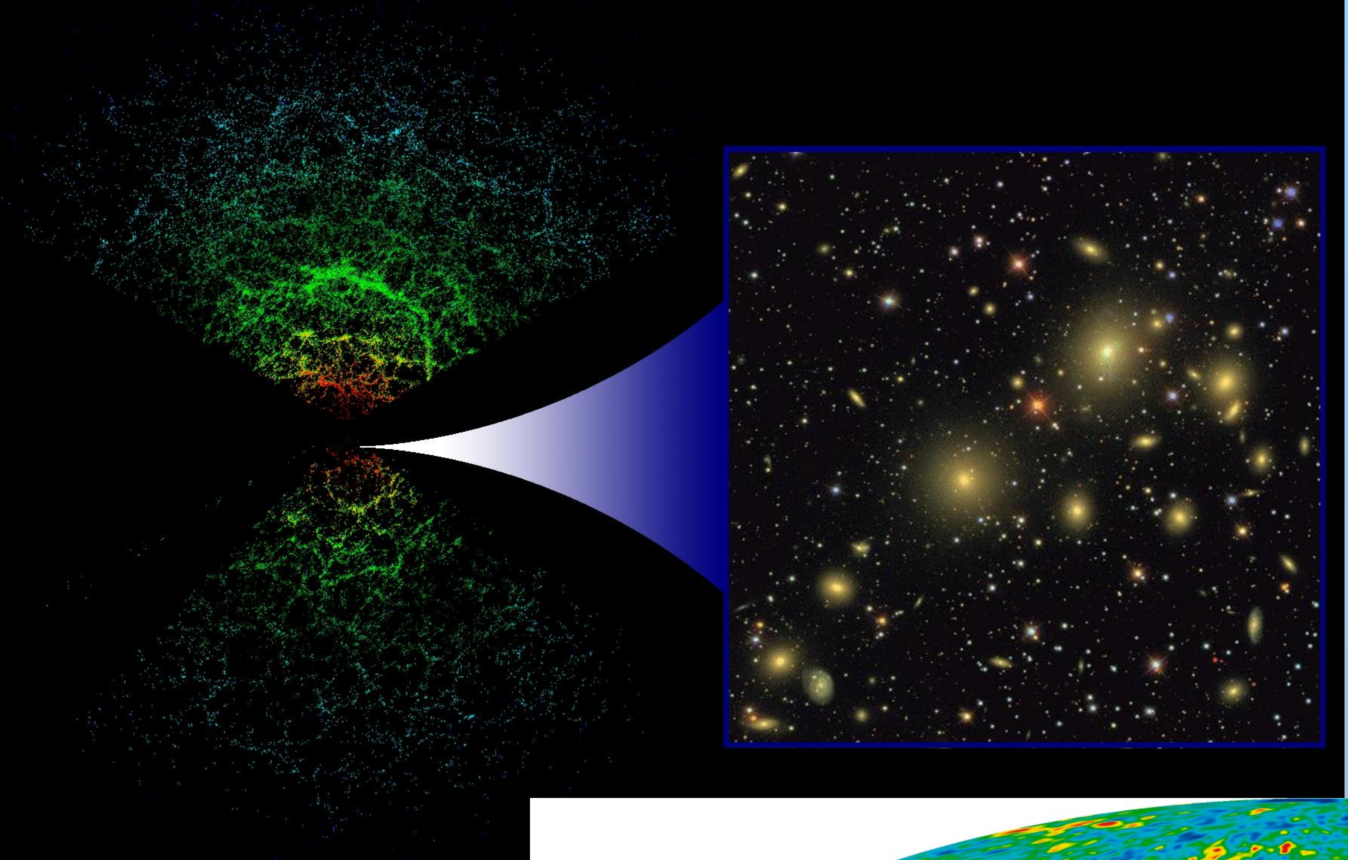


Cosmic deuterium abundance measured in Ly-alpha absorbers gives baryon density
compare with total matter density

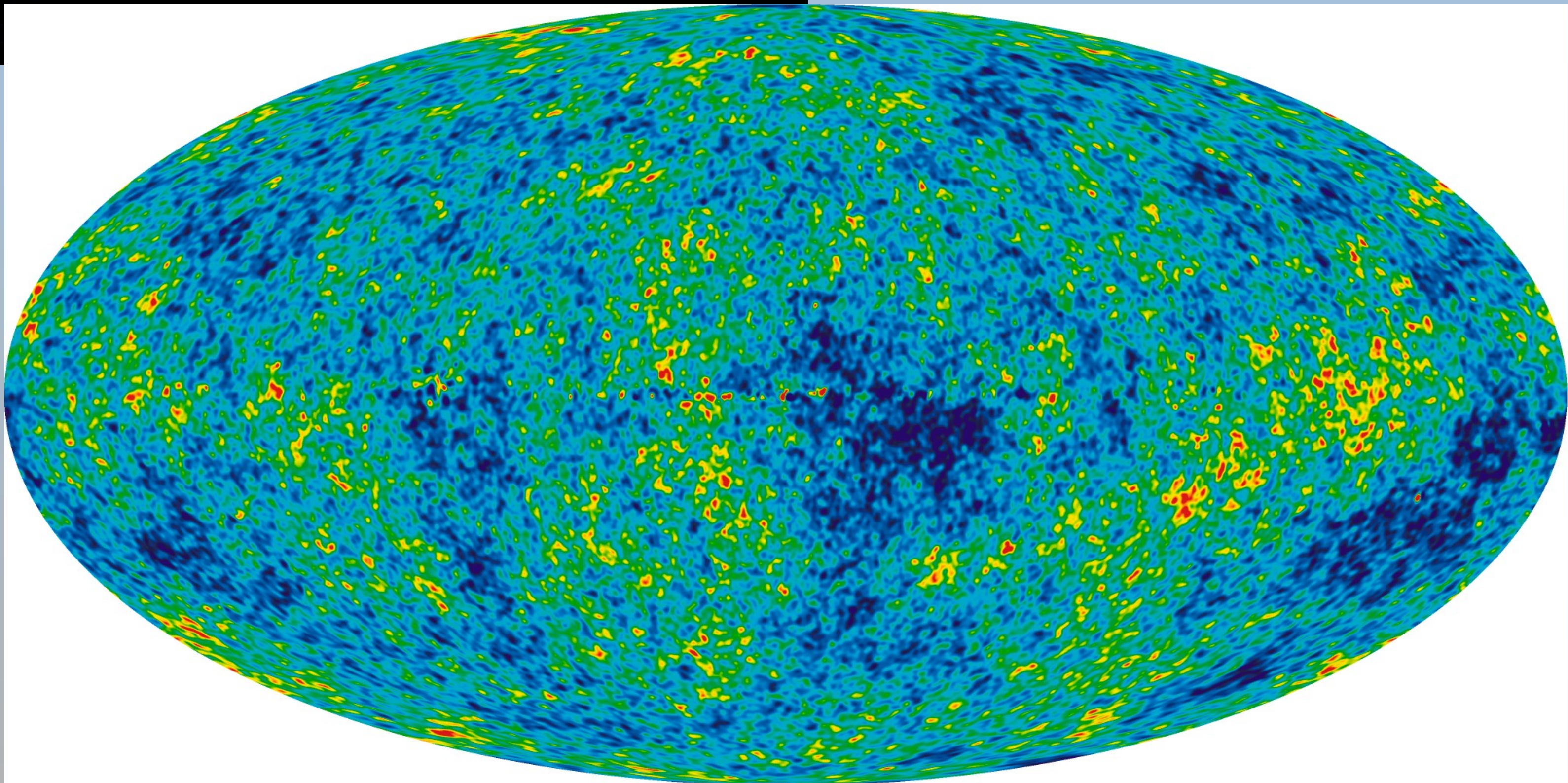
Dark Matter At Large Scales

Pattern of fluctuations determined by dark matter and baryon densities

CMB: the universe is flat!



SDSS

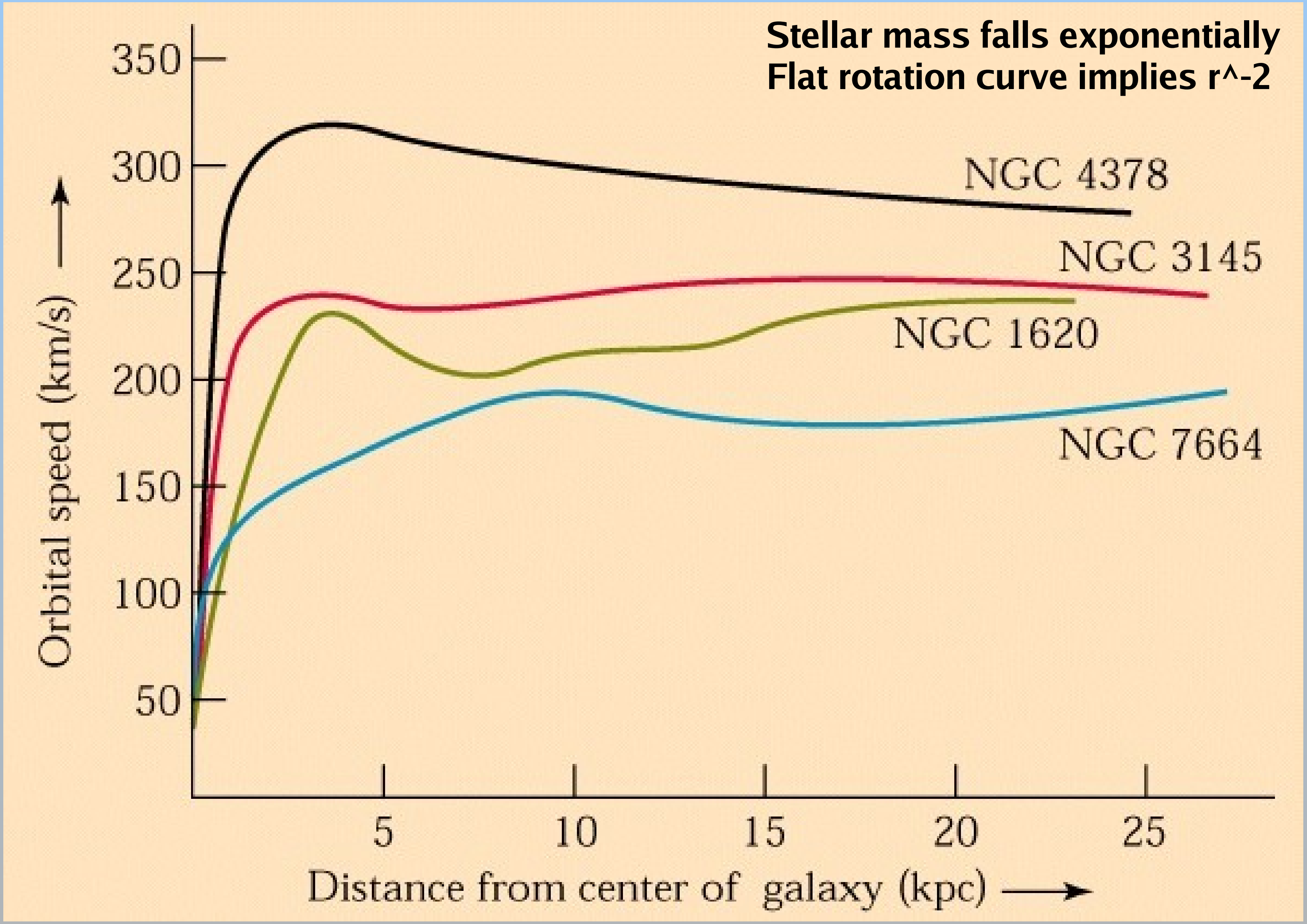


These fluctuations have the same origin (but are viewed at different times)

WMAP

Edward A. Baltz (KIPAC, SLAC)

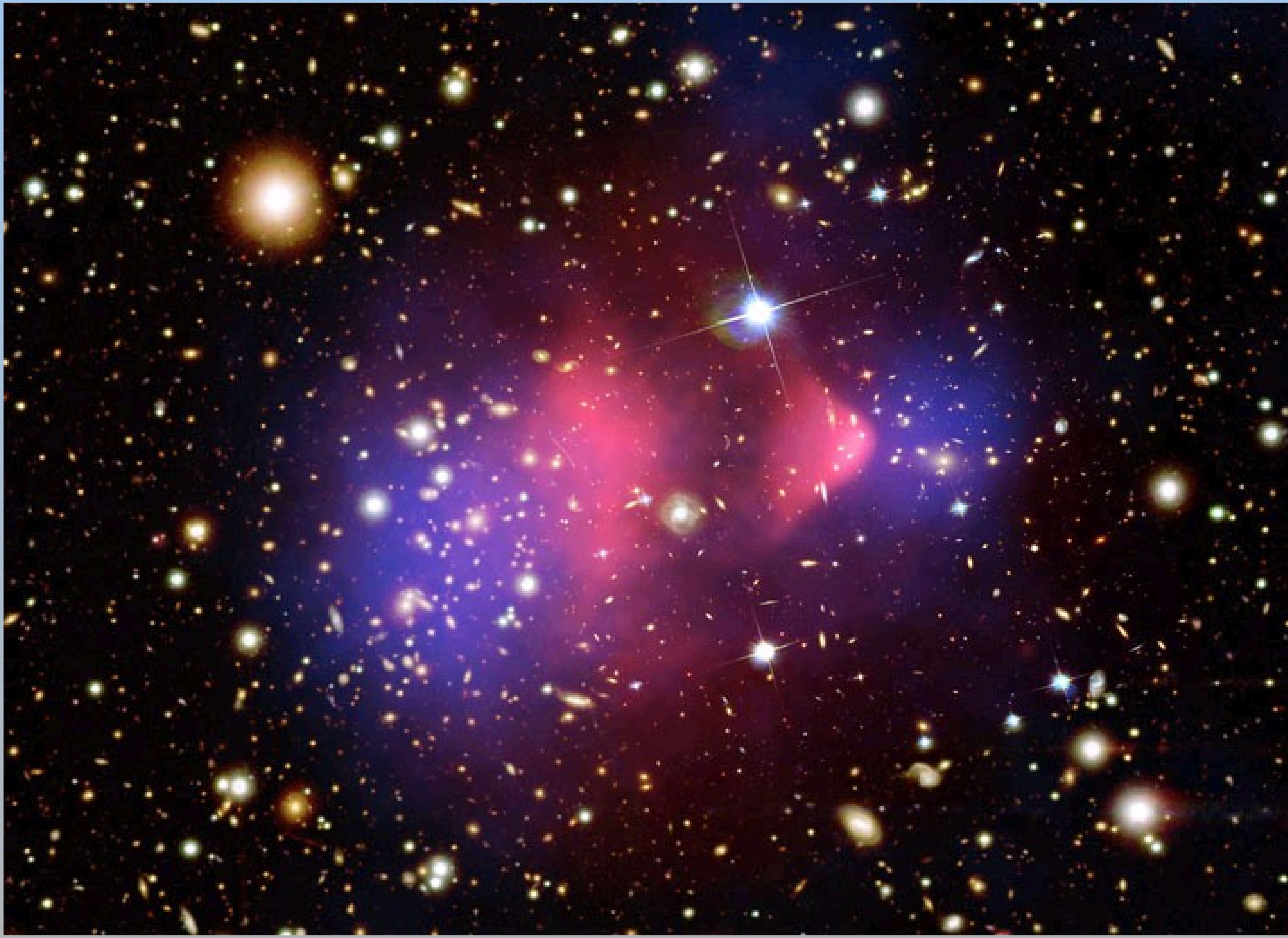
Spiral Galaxy Rotation Curves



Is Dark Matter a Problem With Gravity?

Baryons and dark matter are spatially segregated in a collision between two clusters – baryons are left behind

Bullet Cluster in optical and X-ray



Red: X-ray gas indicating the position of baryons

Blue: total mass seen by gravitational lensing (weak and strong)

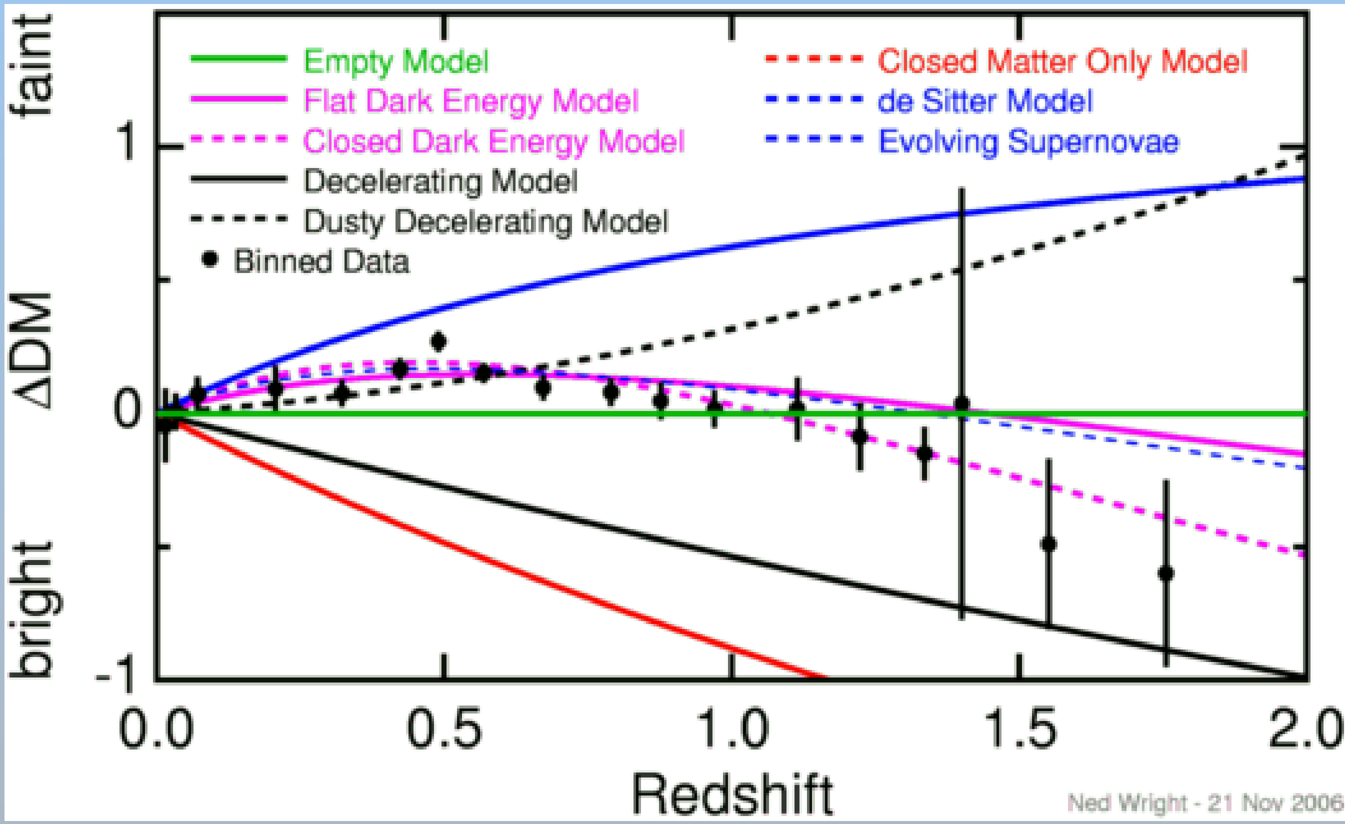
Inferred mass goes with dark matter!

The Accelerating Universe

Type Ia supernovae are standard candles, allowing a measurement of distance versus redshift

The universe is accelerating

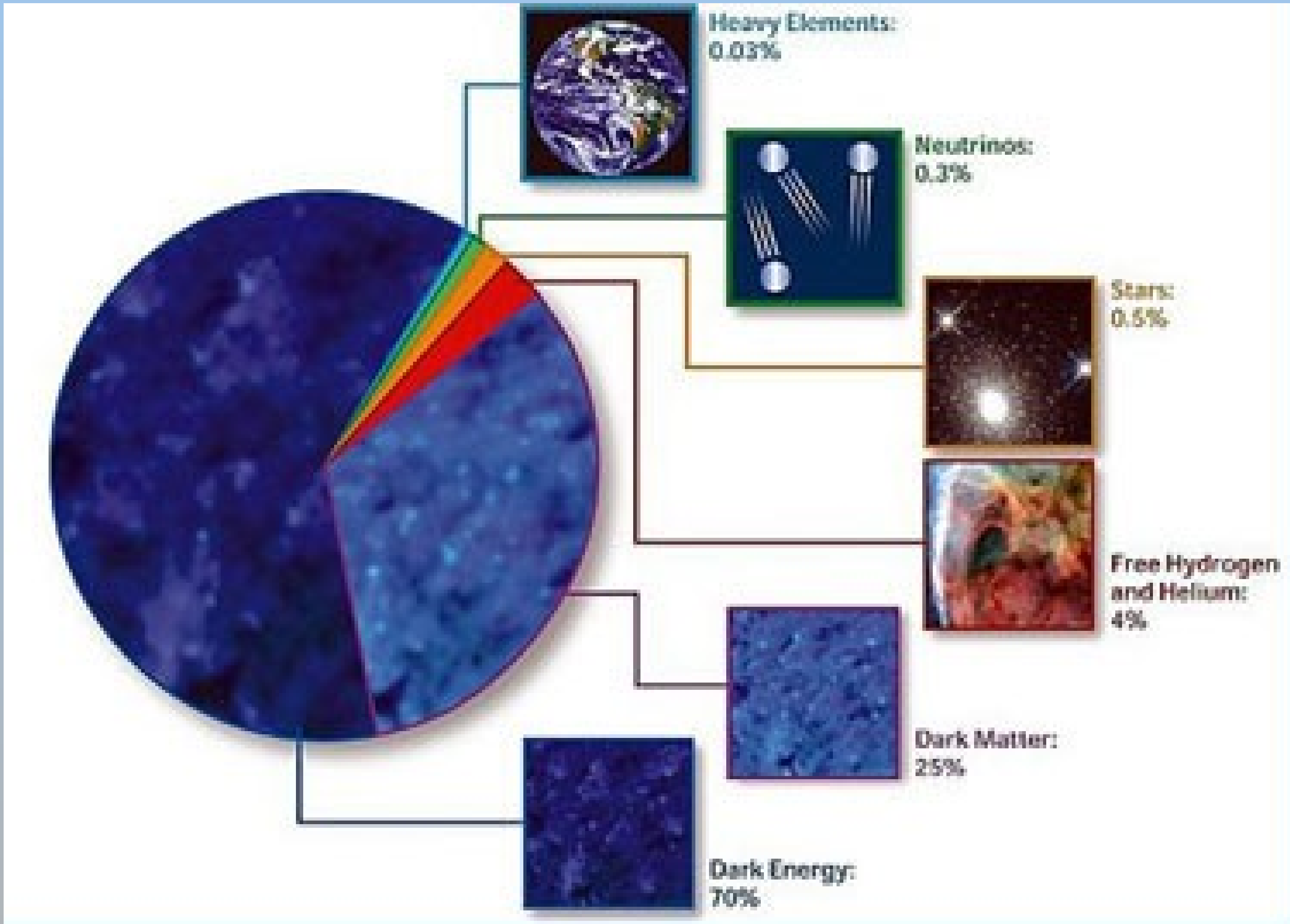
Flat universe with ~70% “dark energy” providing cosmic acceleration



Mass-Energy Budget of the Universe

- The energy density of the universe is mostly unidentified
  - Baryons: ~4%
  - Dark Matter: ~25%
  - Dark Energy: ~70%

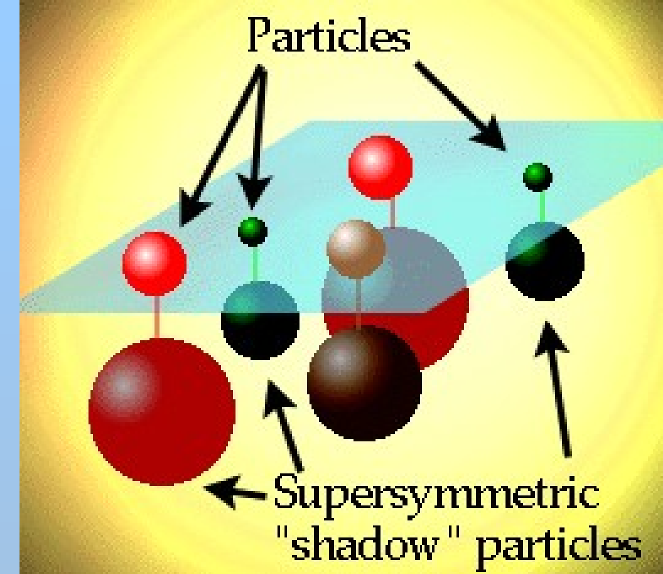
- What is all of this?



Hypothesis: The Dark Matter Consists of Weakly Interacting Massive Particles

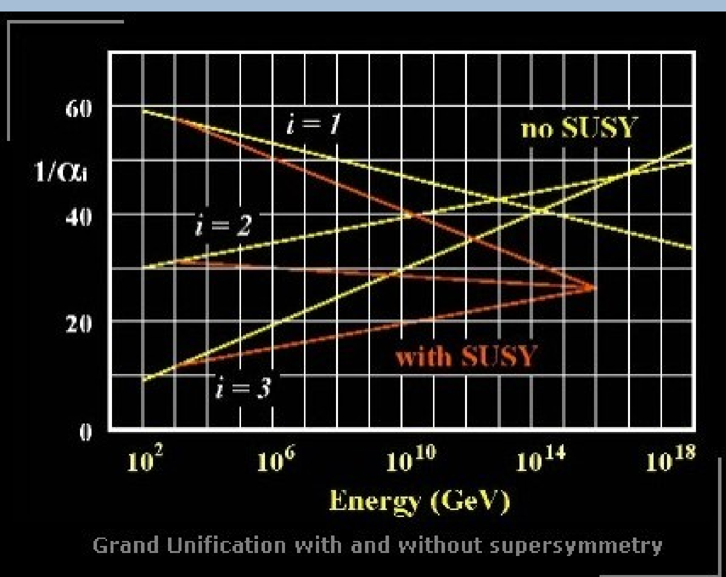
- WIMPs with masses 100 GeV – 1 TeV and typical couplings have annihilation cross sections of order 1 pb
  - this is exactly what is required to give the measured relic abundance with a thermal freeze-out in the hot big bang model
- The weak scale is thus naively related to dark matter
  - a compelling coincidence!
- How can we test this hypothesis?

Supersymmetry: A Model With WIMPs



Boselab

- Proposed extension to the Standard Model
  - relates fermions to bosons
  - SM states have "superpartners"
    - scalar quarks and leptons
    - spin ½ "gauginos" and "Higgsinos"
- If SUSY is broken at the electroweak scale, the hierarchy problem is cured
- Coupling constant unification for free!
- Lightest superpartner is absolutely stable in the simplest implementations of SUSY
  - If electrically neutral, an excellent candidate for dark matter – photino, zino, higgsino



Grand Unification with and without supersymmetry

To Solve the Dark Matter Problem We Must Do Three Things

- 1.) Demonstrate that the dark matter in the galaxy is made of particles
- 2.) Create dark matter candidates in the controlled environments of accelerators
- 3.) Demonstrate that these two are the same
- To accomplish this we need to combine data from astrophysics and accelerators
  - Any one of these three would be a discovery of fundamental importance!

What if WIMPs are observed at the Tevatron or the LHC?
(and what is the astrophysics of WIMPs?)

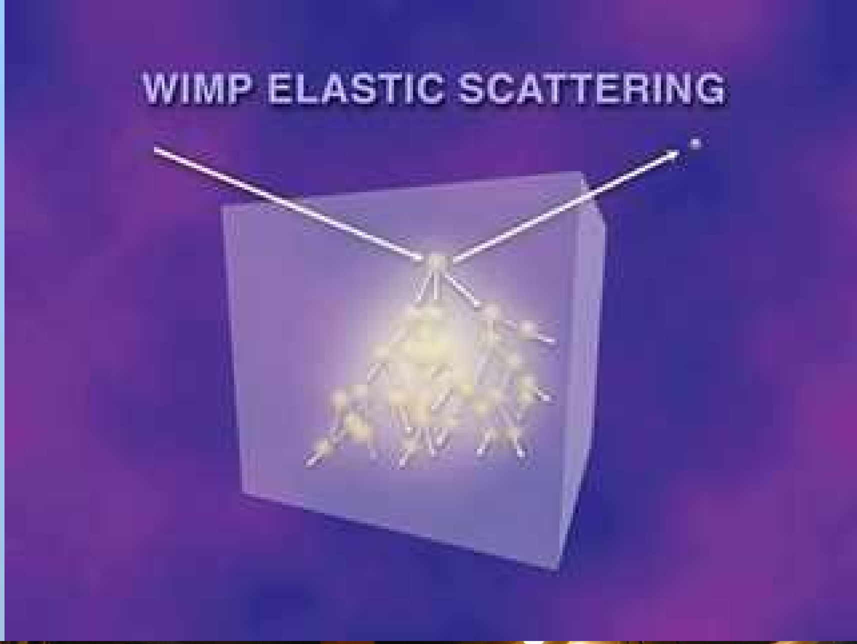
- The WIMP is all / part / none of the dark matter
- The WIMP is stable / unstable to a superWIMP (e.g. gravitino)
- The underlying physics is SUSY / extra dimensions / TBD

- Cosmology was standard / exotic to temperatures of 100 GeV
- The dark matter halo of the galaxy is clumpy / smooth
- The velocity distribution of dark matter is smooth / has features

- We need the data that will distinguish all of these possibilities.

Direct Detection of Dark Matter

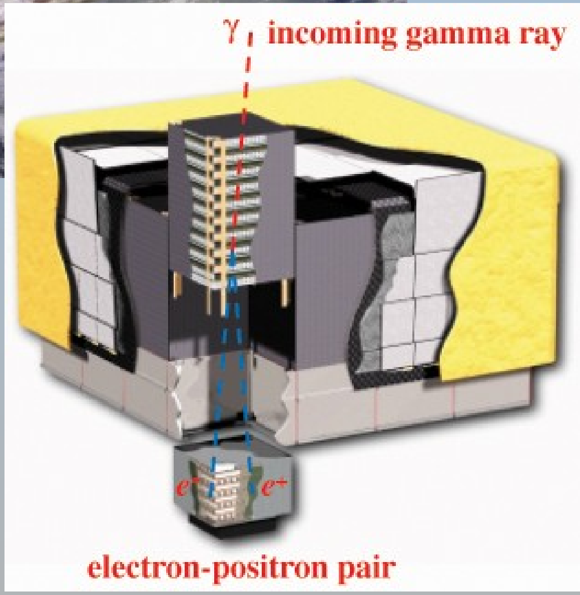
- WIMPs scatter elastically from atomic nuclei
  - ~50 keV deposited
  - many techniques to record energy and distinguish bkg.
    - semiconductors
    - scintillators
    - liquid noble gases
    - bubble chambers
    - TPCs
  - deep underground
- Most techniques measure only the recoil energy
- Recoil direction is more difficult, but possible
- Local flux of WIMPs



CDMS fridge + icebox @ Soudan mine

Indirect Detection of Dark Matter

- Annihilations in galactic halo produce energetic particles
  - photons (gamma rays)
  - antiprotons, antideuterons
  - Positrons
- Density structure of galactic halo
  - Annihilations ~ density squared
- Gamma rays propagate directly
  - GLAST satellite will perform an all-sky survey between 20 MeV and 300 GeV
- GLAST launch ~ October!



GLAST satellite with schematic of LAT instrument

Atmospheric Cerenkov Telescopes

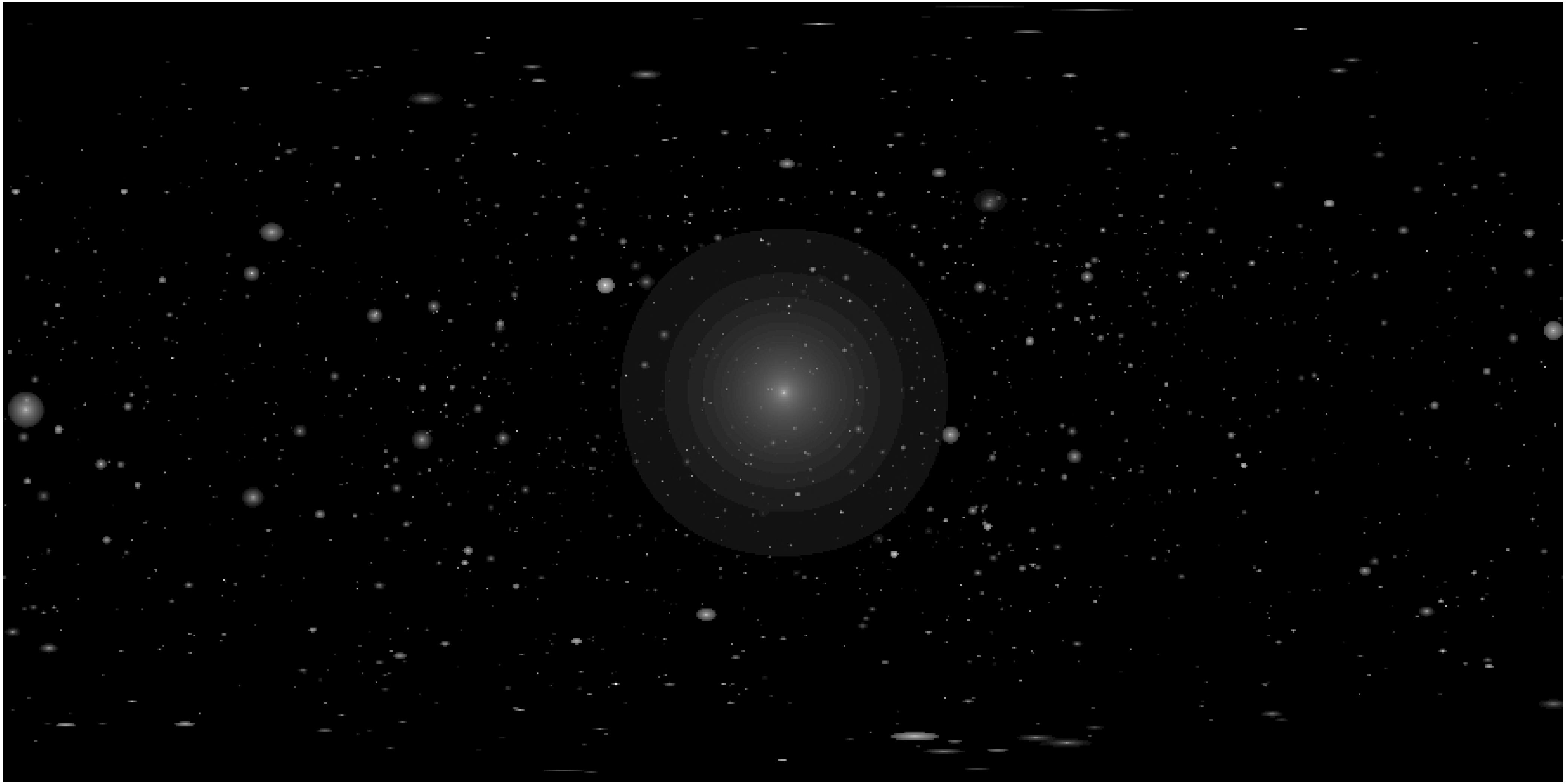
- Gamma-ray astronomy from the ground
- Threshold ~ 100 GeV
- High mass WIMPs required for visibility
- Huge effective area, small field of view
- HESS, VERITAS, MAGIC
- Follow-up of GLAST sources possible

HESS array in Namibia (galactic center visible)

Dark Matter in the Gamma Ray Sky

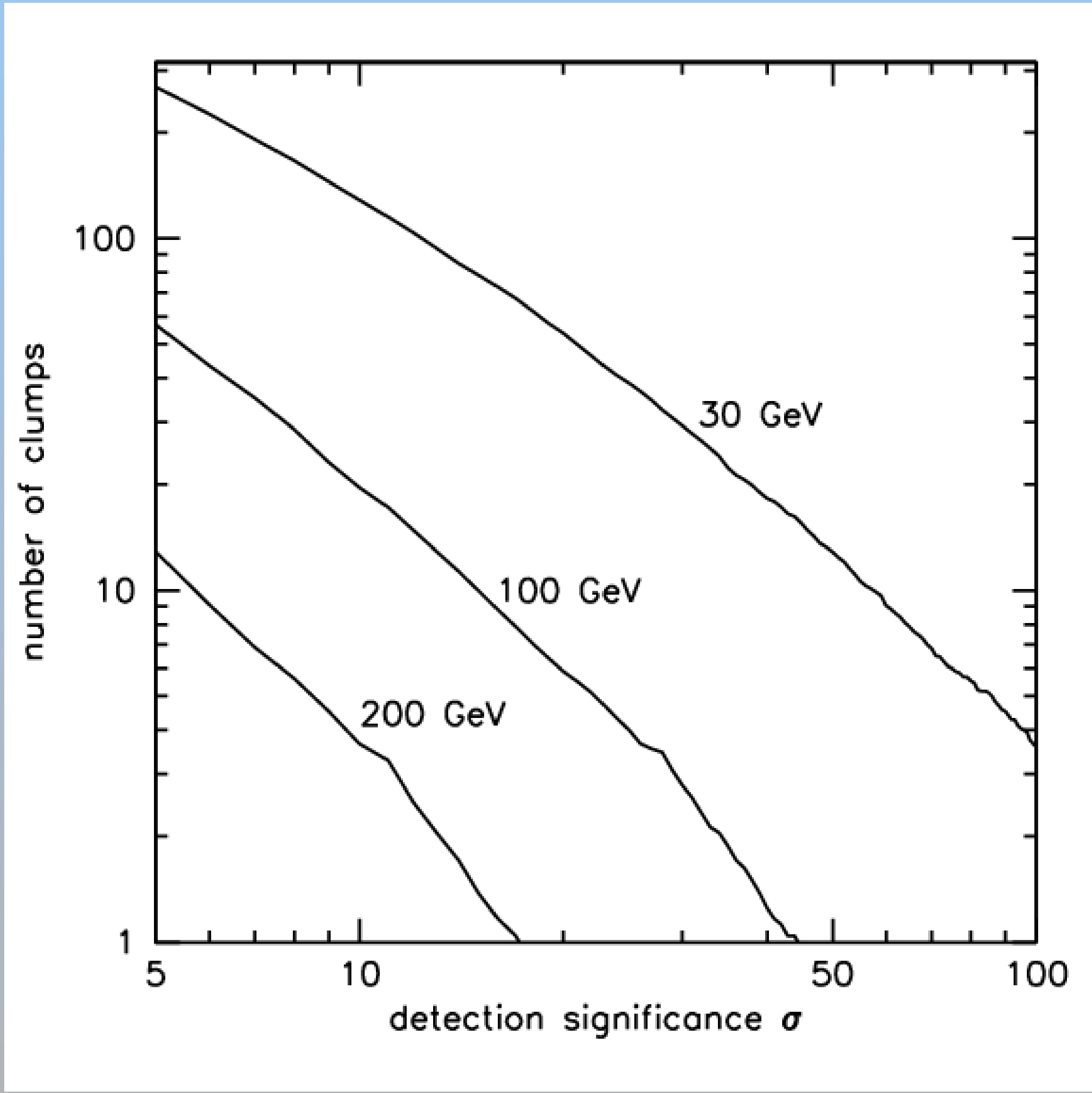
Milky Way Halo simulated by
Taylor & Babul (2005)
All-sky map of gamma ray emission
from dark matter annihilations

Galactic center is brightest,
substructure clearly visible



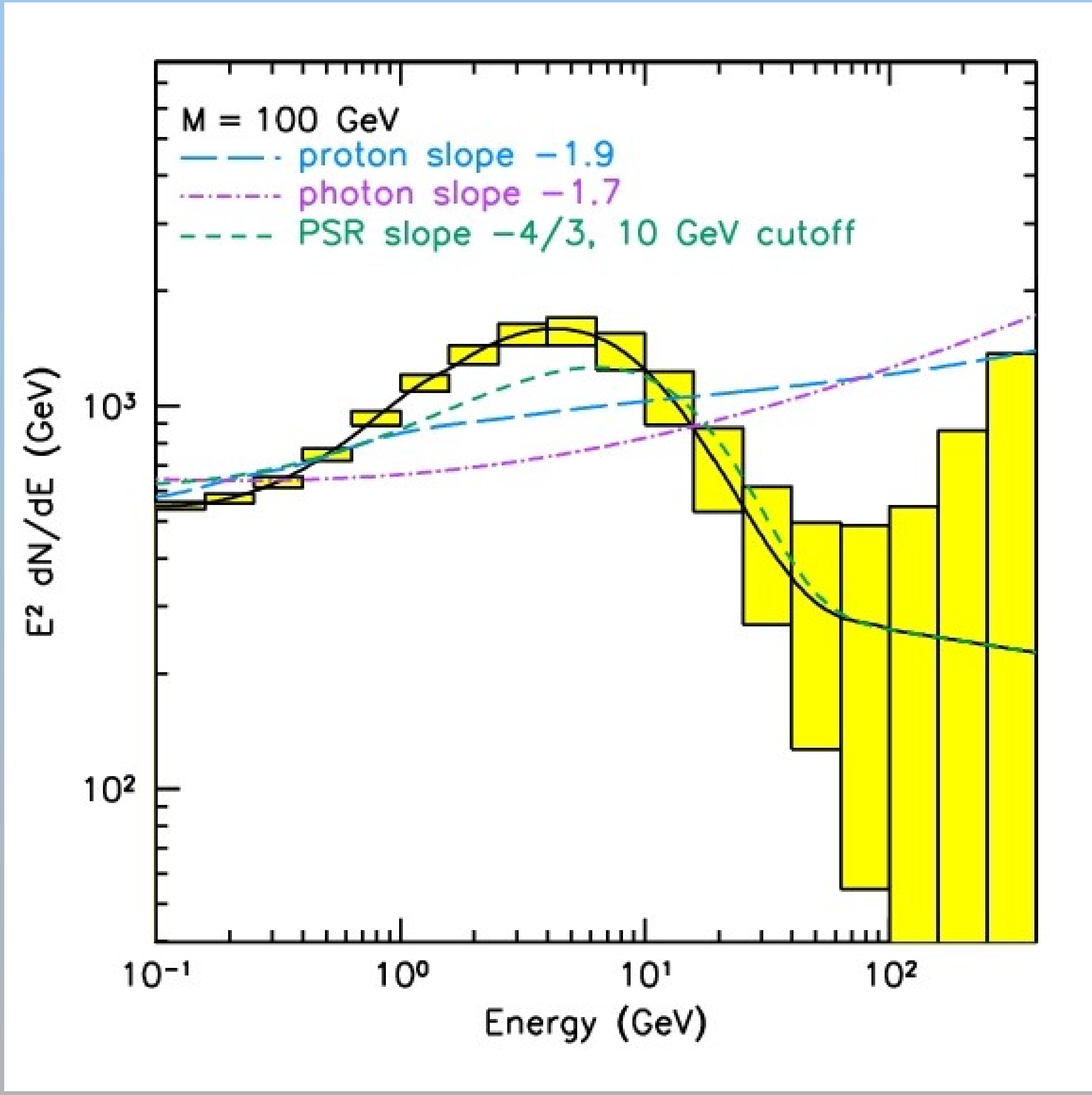
Substructure In the Galactic Halo

- Spectrum of halo sub-structure roughly M^-2
- Density profiles are 1/r, giving "surface brightness" proportional to 1/r
  - With a size of 1 degree, resolved by GLAST!
- Detectable objects can be low-mass (~million M_sun), tidally stripped (100 pc) and nearby (few kpc)



Gamma Ray Spectrum from Dark Matter Annihilations

- **Hadronization produces pions, decaying into high energy photons**
- **Bright GLAST sources distinguishable from astrophysical objects**
  - **Gamma-ray pulsars are the most troublesome**
  - **25% mass measurement at 100 GeV possible**
  - **Gamma ray spectrum AND spatial extent**

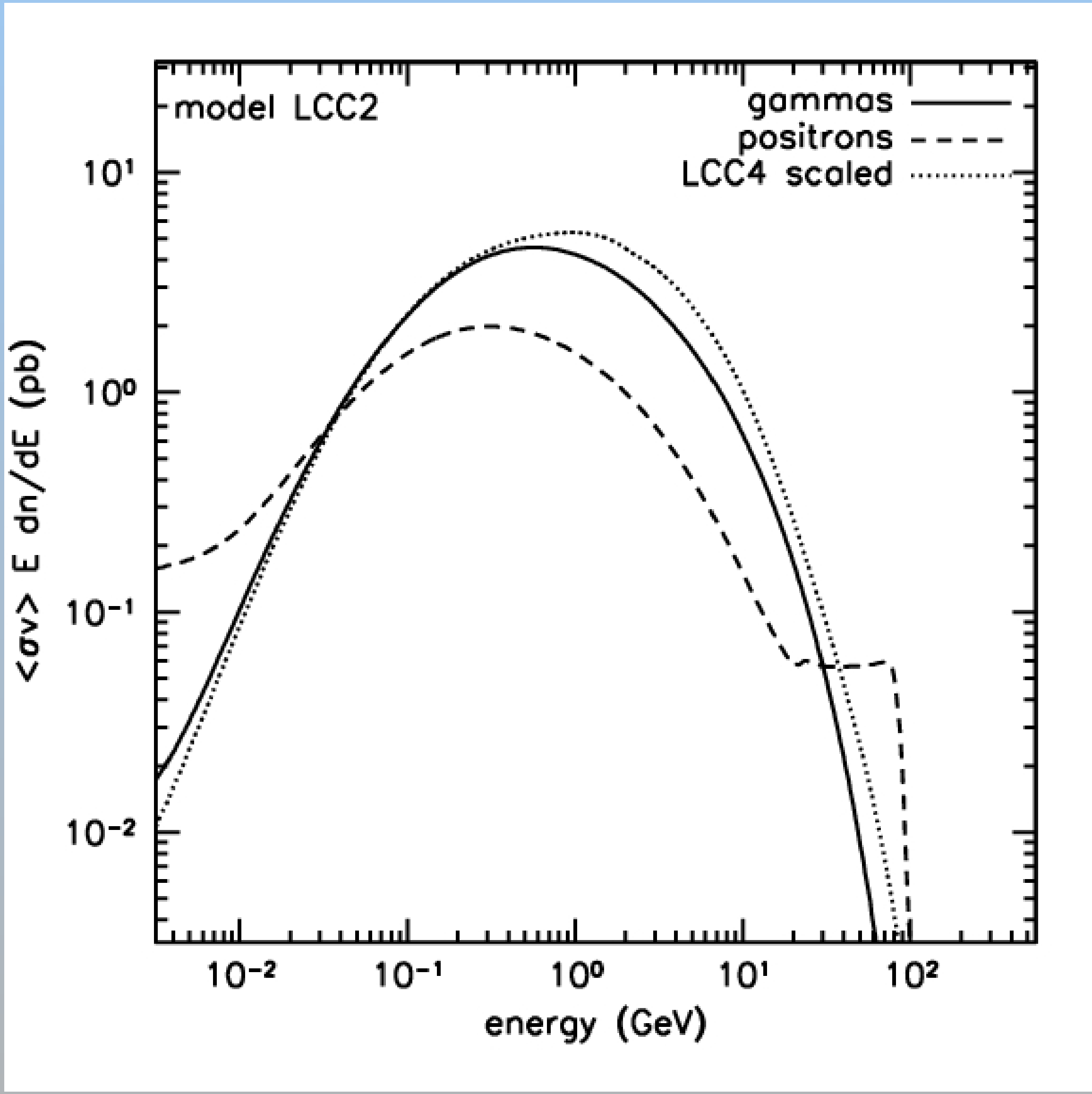


Particle Physics with GLAST

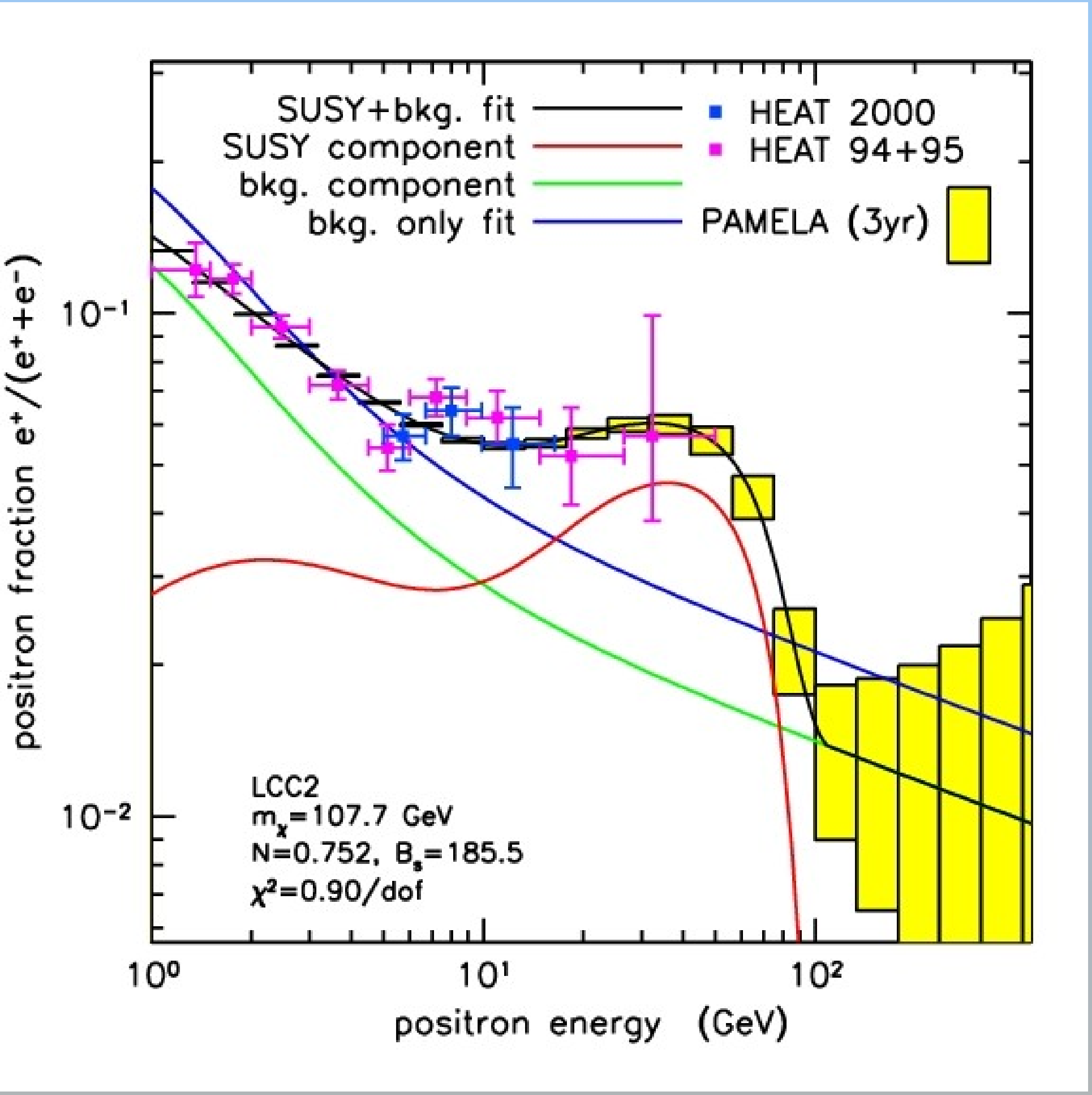
- Astrophysical uncertainties dominate: we would in fact like to measure the dark matter density using collider inputs
- Not much information in spectral shape (besides WIMP mass) – shape is universal over hadronic channels (even W's, Z's)
  - One exception: annihilation to taus gives very hard spectrum, but this is difficult to arrange in SUSY
- There may be information in branching ratios – astrophysical densities cancel
  - line / continuum ratio is the line branching fraction, a function only of the parameters in the Lagrangian
  - line ratio 2 gamma vs. Z gamma is similar

Positrons From Annihilations

- Spectral features can survive galactic effects (diffusion, synchrotron, IC)
  - shelf from W, Z decay
  - lines possible in KK models
- Peak in positron spectrum is difficult to arrange by astrophysical means
- HEAT reports an excess of positrons around 10 GeV
  - Annihilation component?
- PAMELA satellite
  - launched last June
  - Large improvement in sensitivity to ~10 GeV positrons, antiprotons



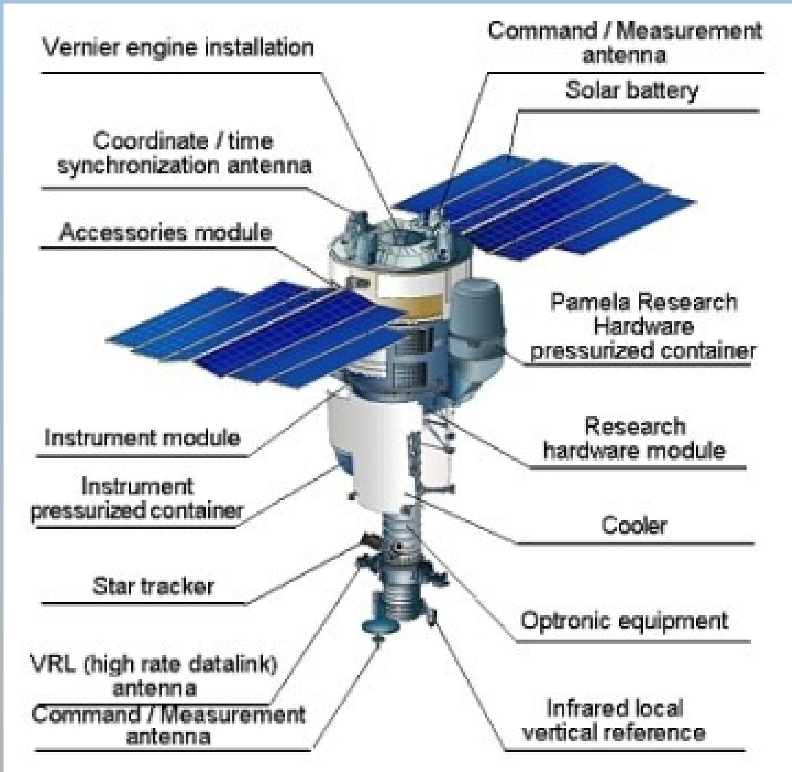
Current and Near-Future Cosmic Ray Positron Data



Fitting the HEAT positron excess requires SUSY signal enhancement of ~ 100x

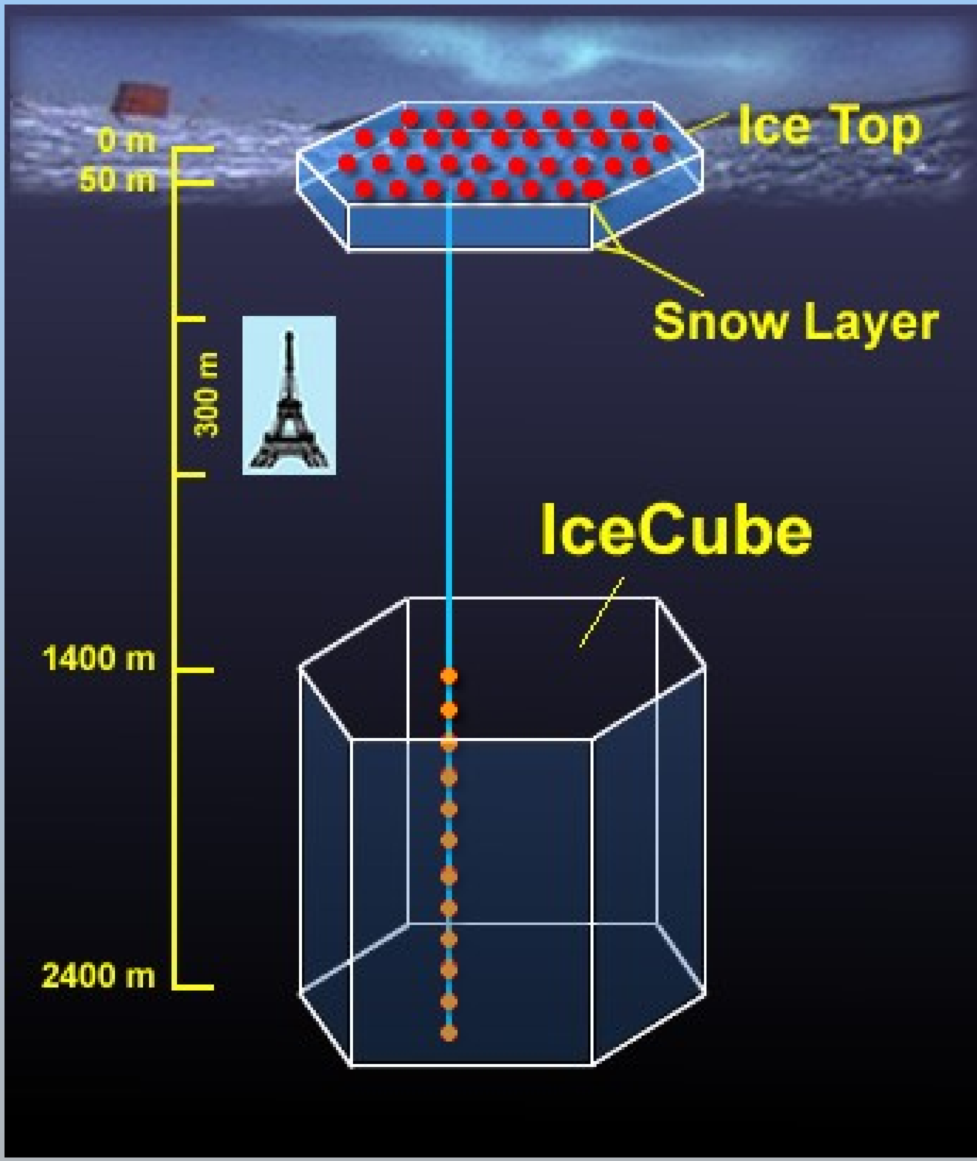
PAMELA will sort this out

Much smaller signals will be accessible to PAMELA!



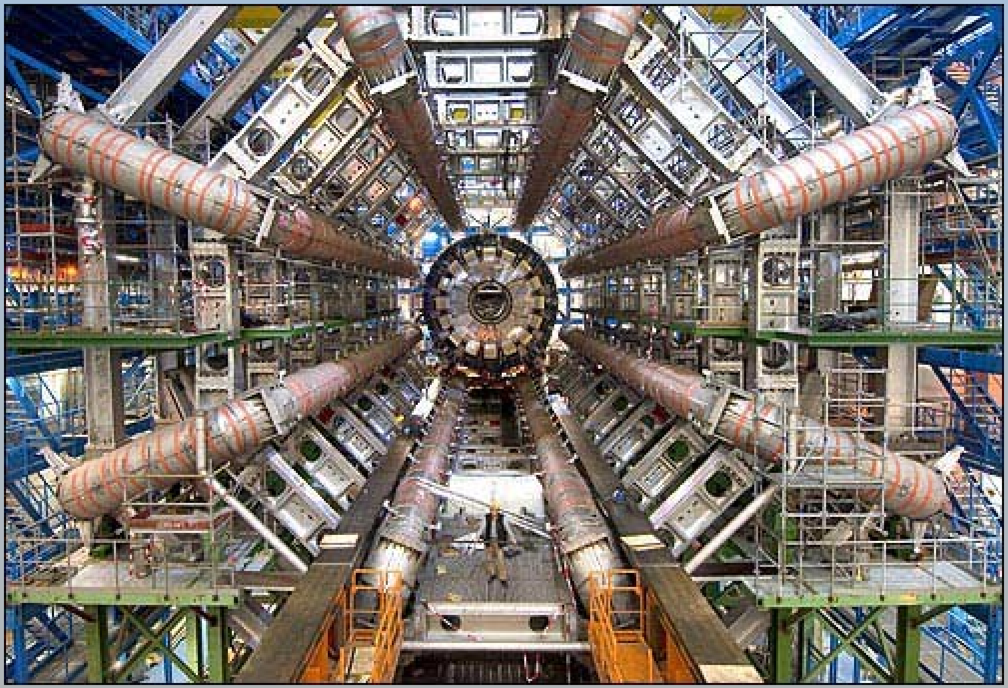
Neutrino Telescopes

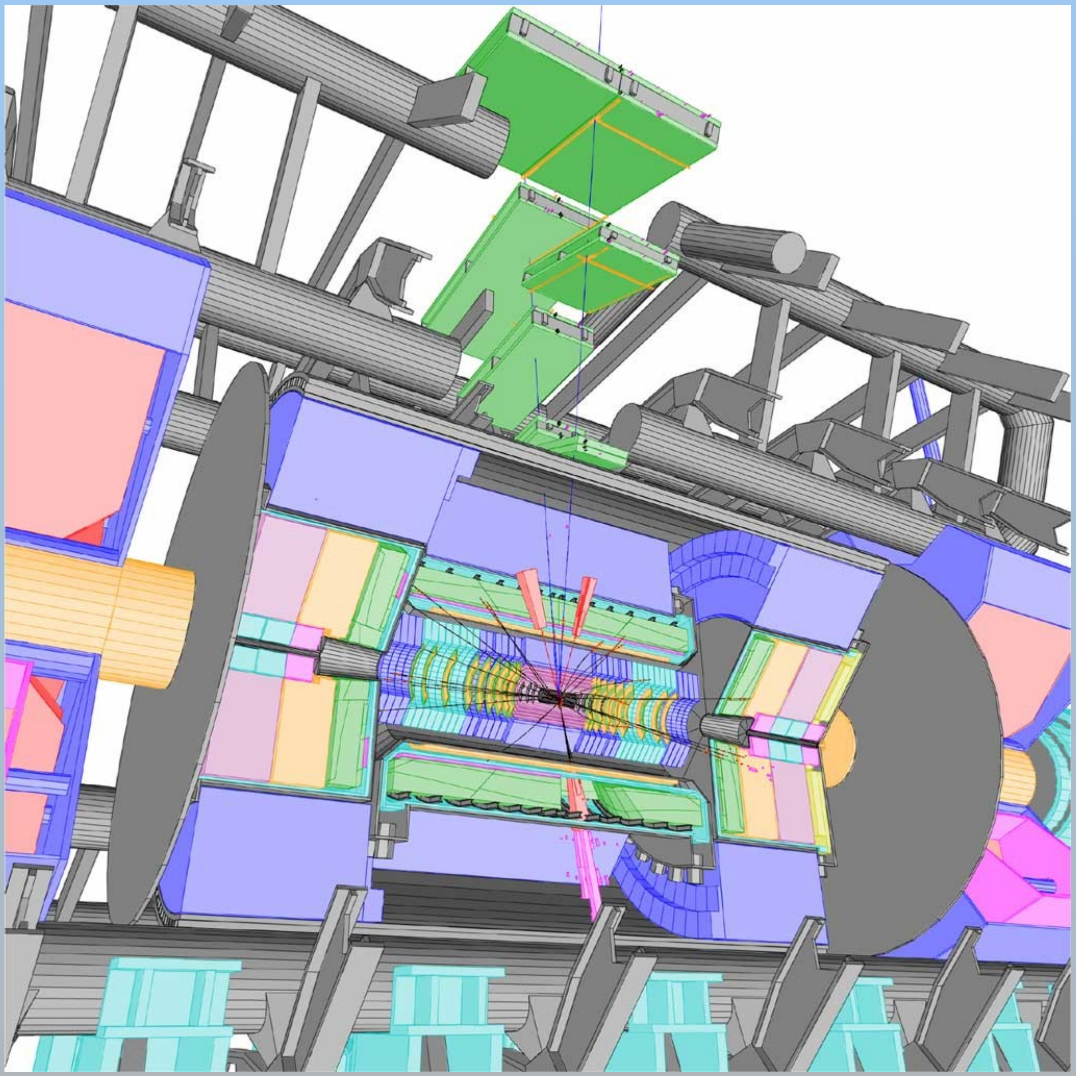
- WIMPs scatter on nuclei, can be captured in bound gravitational orbits
  - Earth, Sun
- WIMPs collect at the centers of these objects and annihilate
  - Only neutrinos escape
- Neutrino telescopes might see this (AMANDA, IceCube, ANTARES)
- Dark matter density averaged along the Sun's galactic orbit



Laboratory Creation of Dark Matter

- Large Hadron Collider
  - find particles up to 2+ TeV in missing energy events
  - start later this year!
- International Linear Collider
  - mass reach not as high
  - precision measurements





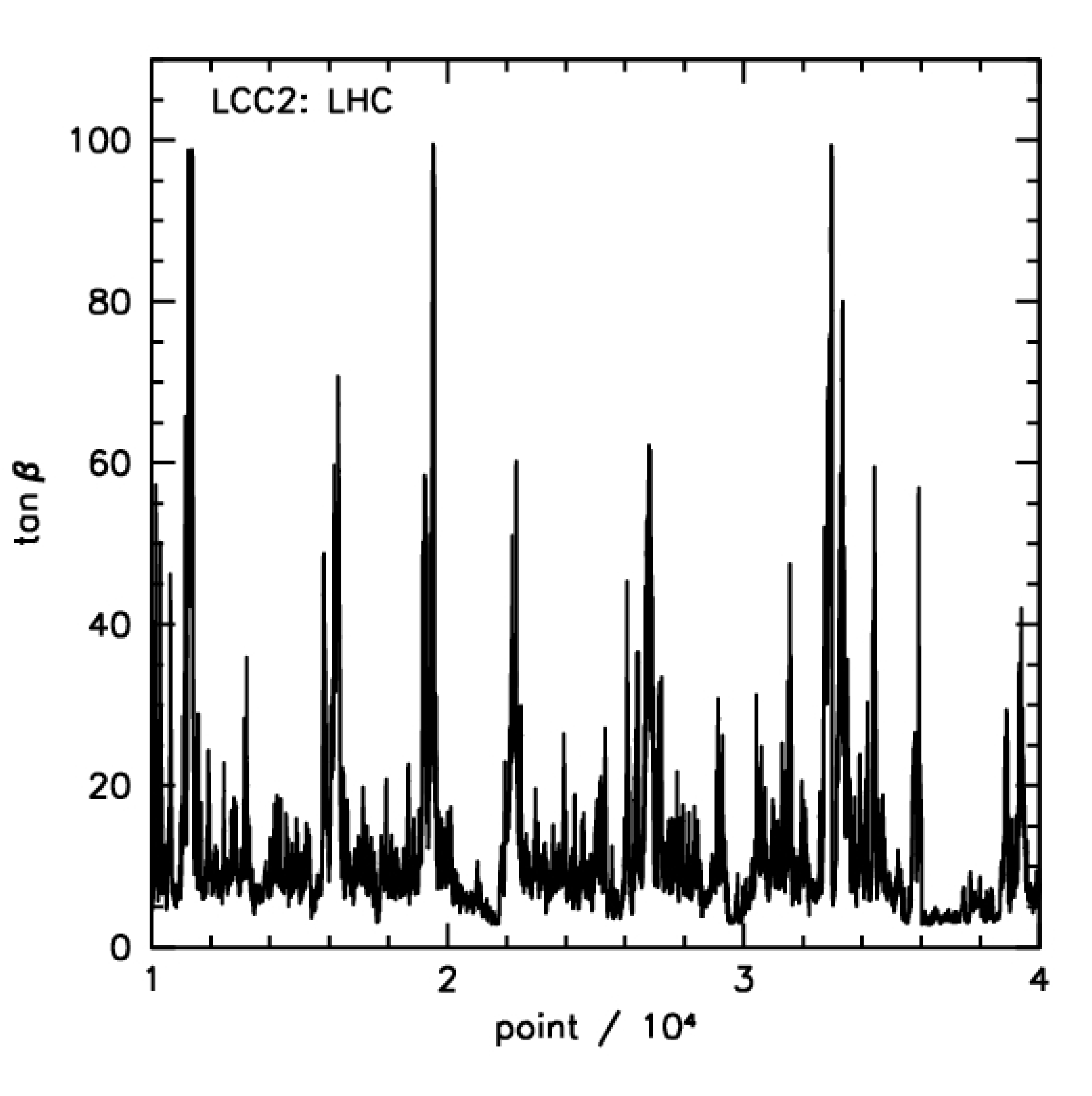
Simulation of event in ATLAS @ LHC

Dark Matter Microphysics

- Much of the discussion is generic to WIMPs, but we take examples from SUSY models
  - EAB, M. Battaglia, M. Peskin and T. Wizansky hep-ph/0602187
- Study 4 “benchmark” SUSY points
  - LCC1-4, chosen by ALCPG: dark matter and ILC-500
- For each of 4 points, identify measurements possible at colliders
  - masses, polarized production cross-sections, FB asymmetries
- For each of 4 points, generate several million SUSY models consistent with simulated measurements
  - 24 parameters – most general MSSM conserving flavor and CP
- Study the predictions of properties relevant to dark matter, given the collider measurements at each benchmark point
- Calculated with ISAJET 7.69 and DarkSUSY 4.1

Sampling High-Dimensional Parameter Spaces

- **Markov Chain Monte Carlo**
  - construct chains of points distributed according to "likelihood function"
  - very efficient if the proposal distribution is well-matched
- **Map out the parameter regions that give acceptable likelihood**
- **Make predictions for unmeasured quantities**
  - this is "just" an exercise in error propagation



Constraints: LCC1 (SPS1a)

cross sections

cross section		LCC1 Value (fb)		ILC 500	ILC 1000
$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	LR	431.5 (0.758)	$\pm$	$1.1\%^*$	
	RL	13.1 (0.711)	$\pm$	$3.5\%^*$	
$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	LR	172.2	$\pm$	$2.1\%^*$	
	RL	20.6	$\pm$	$7.5\%^*$	
$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0)$	LR	189.9	$\pm$	$2.0\%^*$	
	RL	5.3	$\pm$	$10.2\%^*$	
$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-)$	LR	45.6	$\pm$	7%	
	RL	142.1	$\pm$	4%	
$\sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-)$	LR	57.3 (0.696)	$\pm$	6%	
	RL	879.9 (0.960)	$\pm$	1.5%	
$\sigma(e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1)$	LR	9.8	$\pm$		15%
	RL	11.1	$\pm$		14%

mass/mass splitting	LCC1 Value		LHC	ILC 500	ILC 1000
$m(\tilde{\chi}_1^0)$	95.5	$\pm$	4.8	0.05	
$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$	86.1	$\pm$	1.2	0.07	
$m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$	261.2	$\pm$	$@^a$	4.0	
$m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0)$	280.1	$\pm$	2.2^a	2.2	
$m(\tilde{\chi}_1^+)$	181.7	$\pm$	-	0.55	
$m(\tilde{\chi}_2^+)$	374.7	$\pm$	-	-	3.0
$m(\tilde{e}_R)$	143.1	$\pm$	-	0.05	
$m(\tilde{e}_R) - m(\tilde{\chi}_1^0)$	47.6	$\pm$	1.0	0.2	
$m(\tilde{\mu}_R) - m(\tilde{\chi}_1^0)$	47.5	$\pm$	1.0	0.2	
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	38.6	$\pm$	5.0	0.3	
$BR(\tilde{\chi}_2^0 \to \tilde{e}e)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}\tau)$	0.077	$\pm$	0.008		
$m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$	109.1	$\pm$	1.2	0.2	
$m(\tilde{\mu}_L) - m(\tilde{\chi}_1^0)$	109.1	$\pm$	1.2	1.0	
$m(\tilde{\tau}_2) - m(\tilde{\chi}_1^0)$	112.3	$\pm$	-	1.1	
$m(\tilde{\nu}_e)$	186.2	$\pm$	-	1.2	
$m(h)$	113.68	$\pm$	0.25	0.05	
$m(A)$	394.4	$\pm$	*	(> 240)	1.5
$m(\tilde{u}_R)$, $m(\tilde{d}_R)$	548.	$\pm$	19.0	16.0	
$m(\tilde{s}_R)$, $m(\tilde{c}_R)$	548.	$\pm$	19.0	16.0	
$m(\tilde{u}_L)$, $m(\tilde{d}_L)$	564., 570.	$\pm$	17.4	9.8	
$m(\tilde{s}_L)$, $m(\tilde{c}_L)$	570., 564.	$\pm$	17.4	9.8	
$m(\tilde{b}_1)$	514.	$\pm$	7.5	5.7	
$m(\tilde{b}_2)$	539.	$\pm$	7.9	6.2	
$m(\tilde{t}_1)$	401.	$\pm$	(> 270)	-	2.0
$m(\tilde{g})$	611.	$\pm$	8.0	6.5	

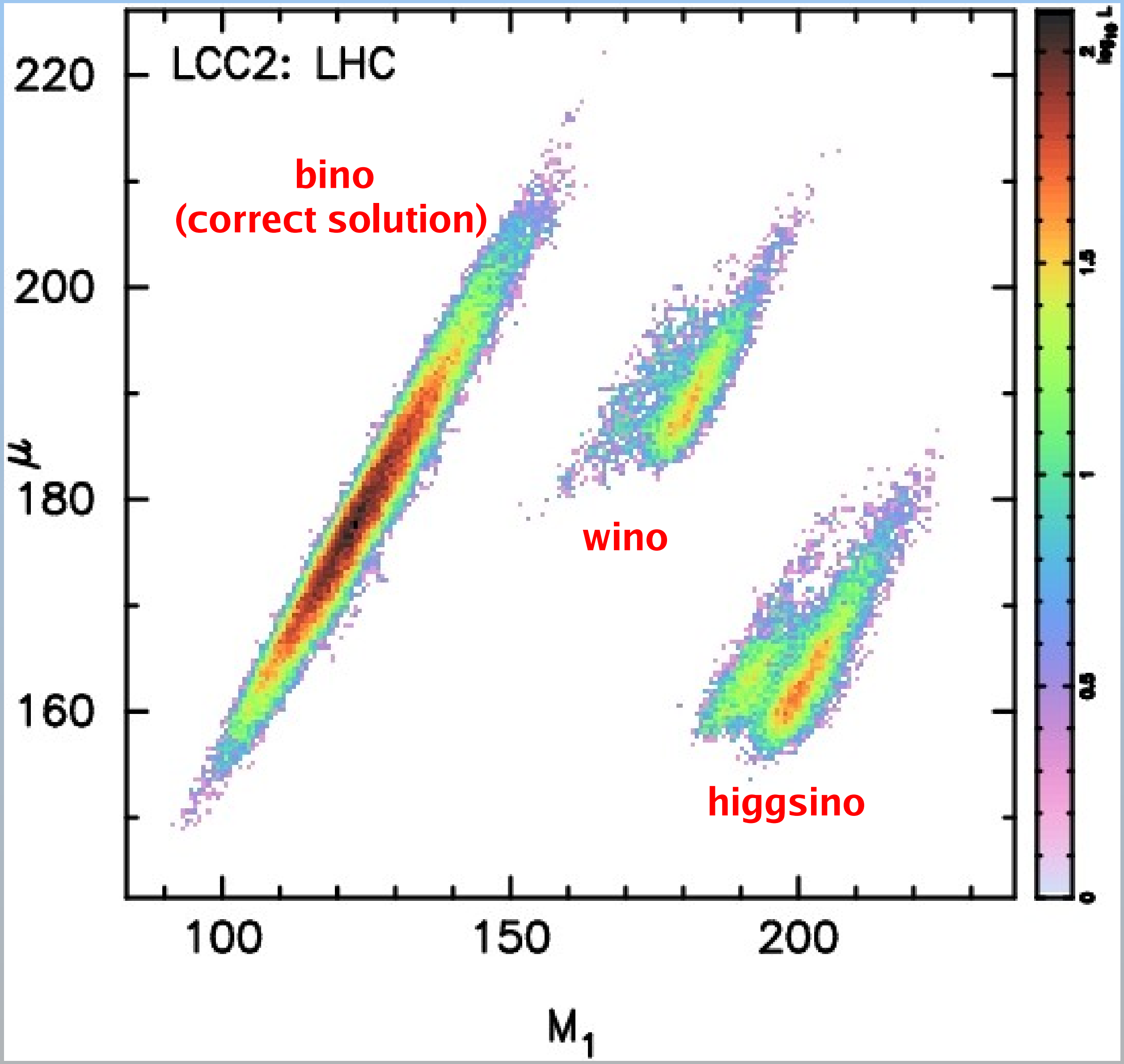
masses

(Weiglein et al., Phys. Rep., 2006)

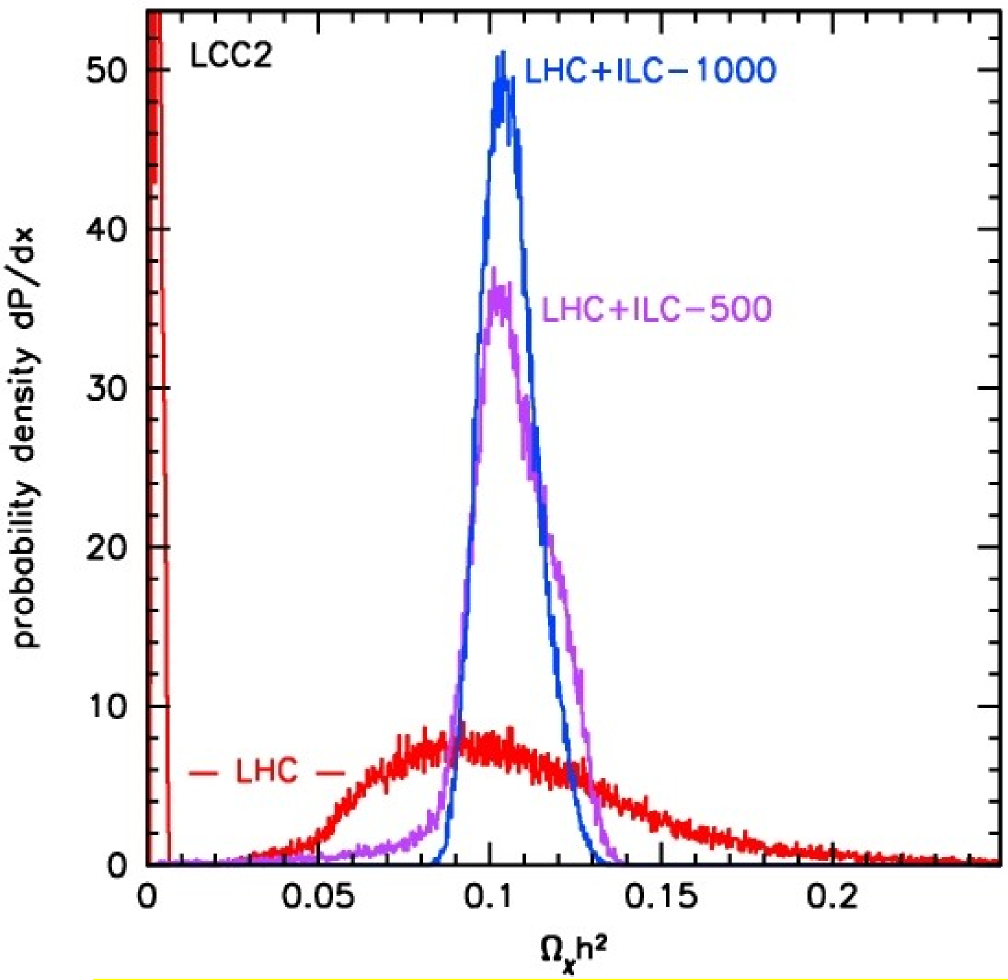
What if LCC2 is the Correct Model of Nature?

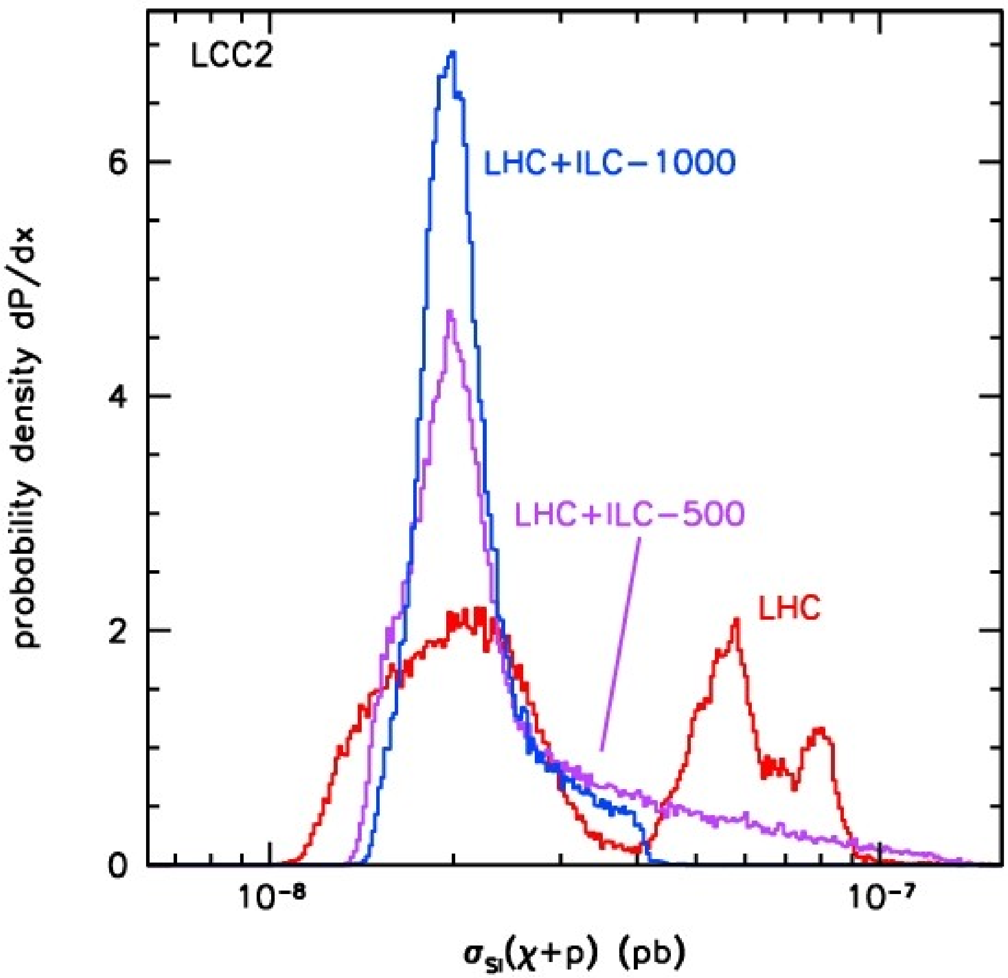
- "Focus point" region: gauginos, higgsinos are light, sfermions are all inaccessible to any collider
  - LHC discovers most gauginos + Higgsinos, one Higgs boson
  - ILC discovers the remaining gauginos + Higgsinos, measures various cross sections
- Relic density prediction has 10% accuracy with ILC TeV
  - CMB measurement (Planck, 0.5%) is doing collider physics!
- Direct detection is dominated by exchange of light Higgs
  - The usually dominant heavy Higgs is so heavy that it's irrelevant
- Annihilation cross section is large – dominated by W pairs
  - promising for gamma ray experiments

LCC2: Probability Islands for Neutralinos @ LHC



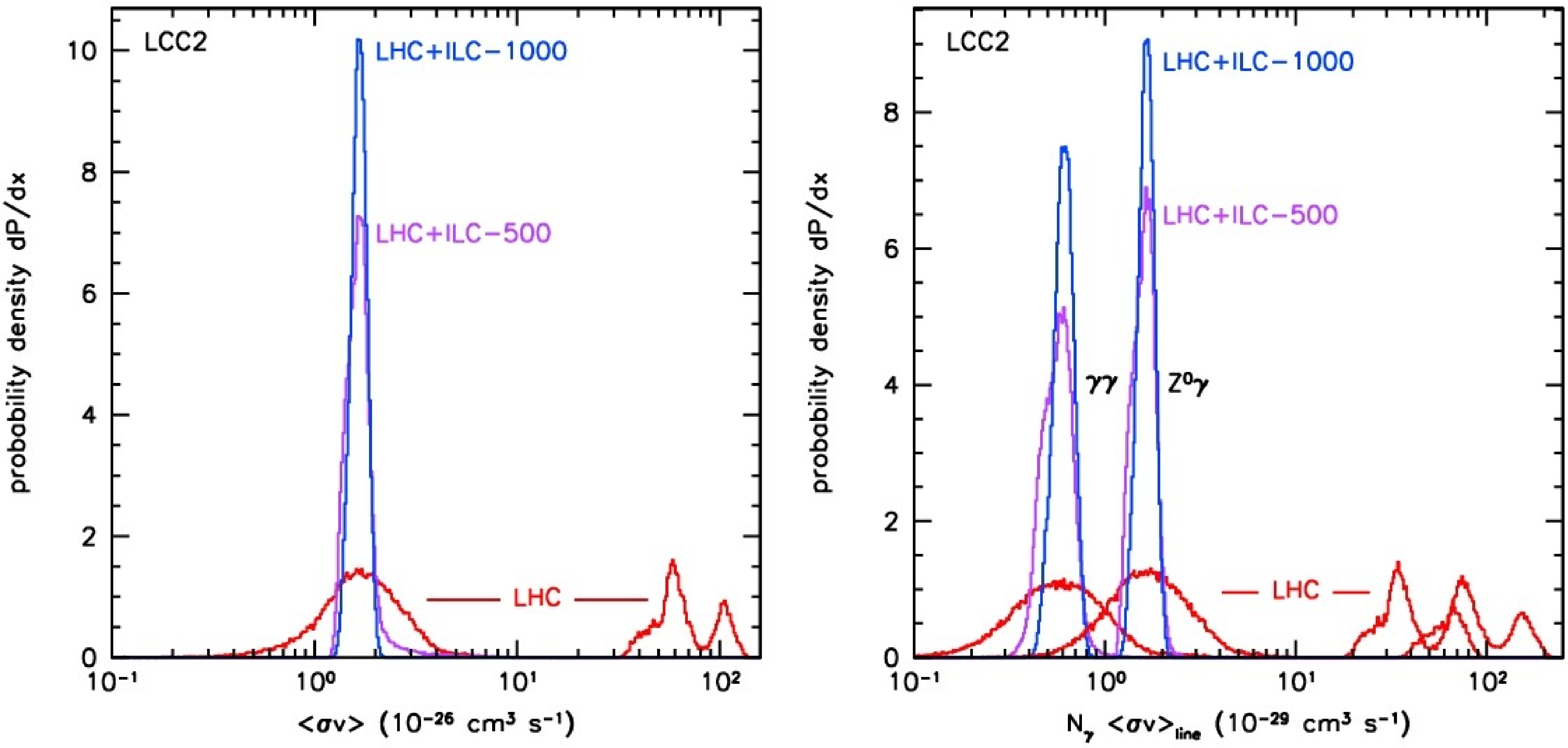
LCC2: Prediction of Relic Density and Direct Detection Cross Section





probability distribution functions for dark matter quantities given possible accelerator measurements and assuming a supersymmetric model

LCC2: Prediction of Annihilation Cross Sections



The Situation in 2012 for LCC2

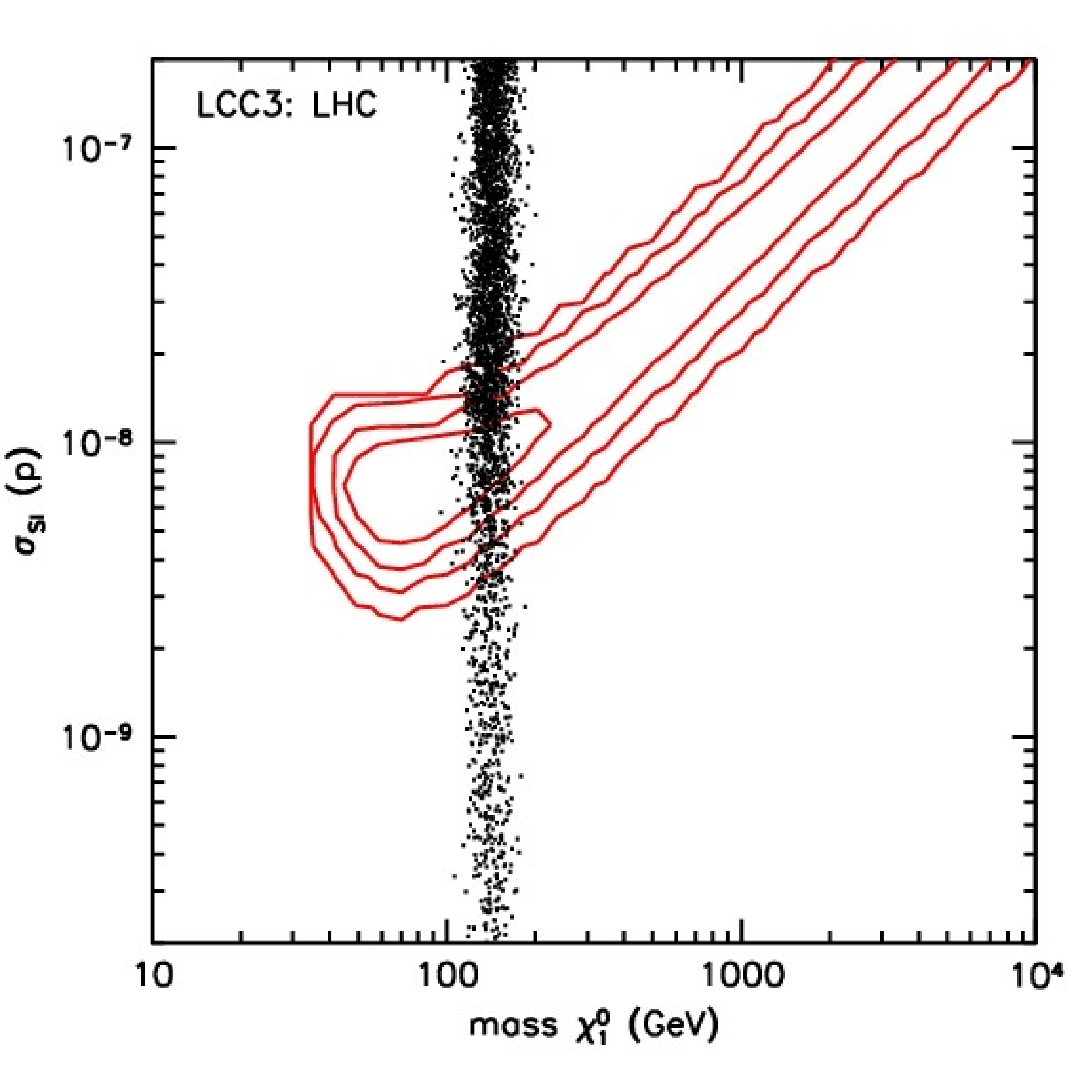
- LHC has seen missing energy events, and measured masses for new particles including a dark matter candidate
  - What is the underlying theory? Spins are difficult to measure.
  - The standard cosmology chooses the SUSY bino solution
- GLAST has obtained a 4+ year sky survey, and has observed anomalous gamma ray sources
  - Inferred mass is in the same range seen at LHC
  - Evidence for galactic dark matter clustering?
- Direct detection experiments have detected ~70 events (SuperCDMS 25 kg), measured mass to 30%
  - Mass is consistent with LHC
  - Measure the local dark matter density, assuming the SUSY solution

Using Direct Detection to Measure Particle Properties

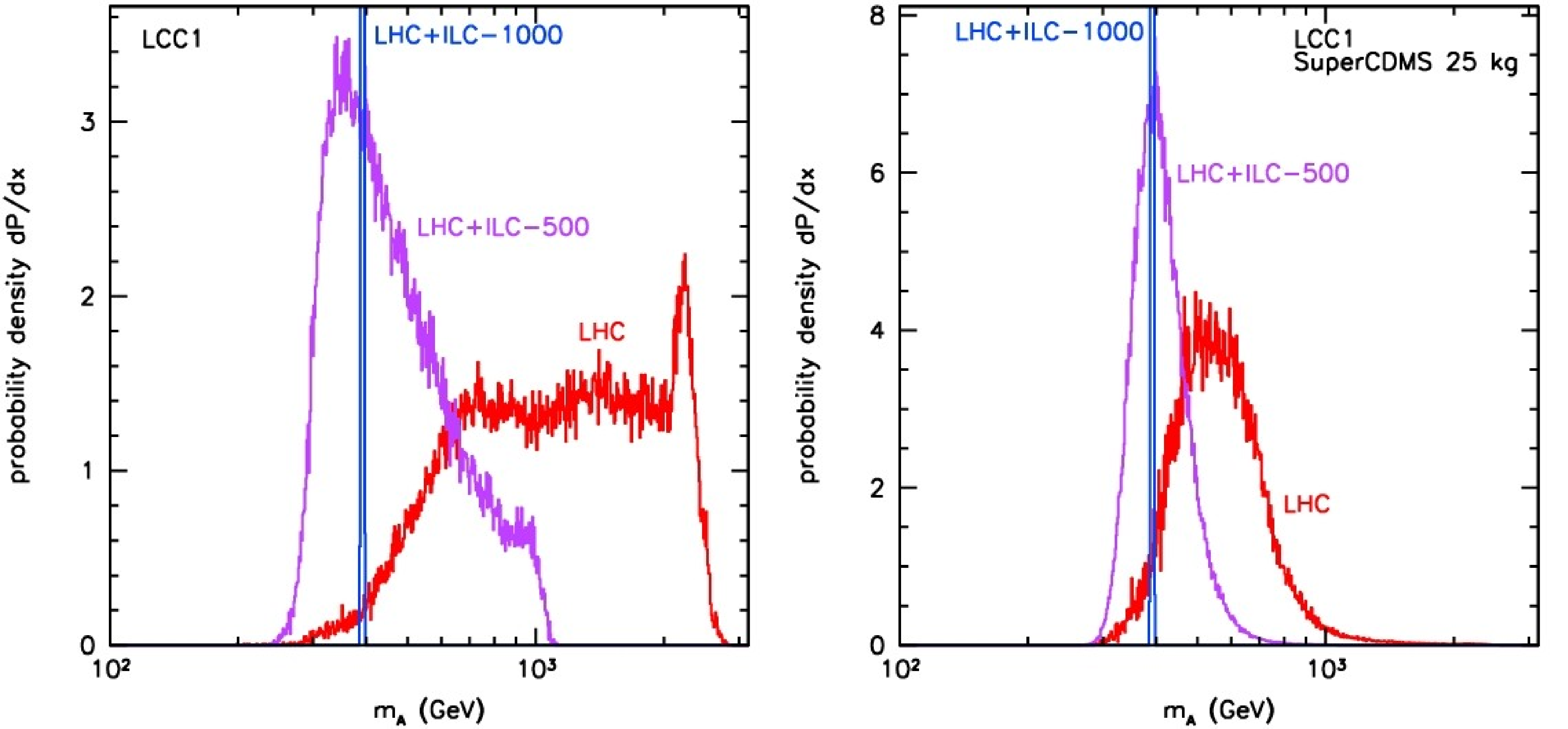
LHC measures the mass, but not the elastic scattering cross section

Direct detection provides this accurately, if given the mass (and assuming the standard galactic halo)

Bottom Line: we can measure masses of Higgs bosons without direct observation



Astrophysical Prediction for Particle Physics



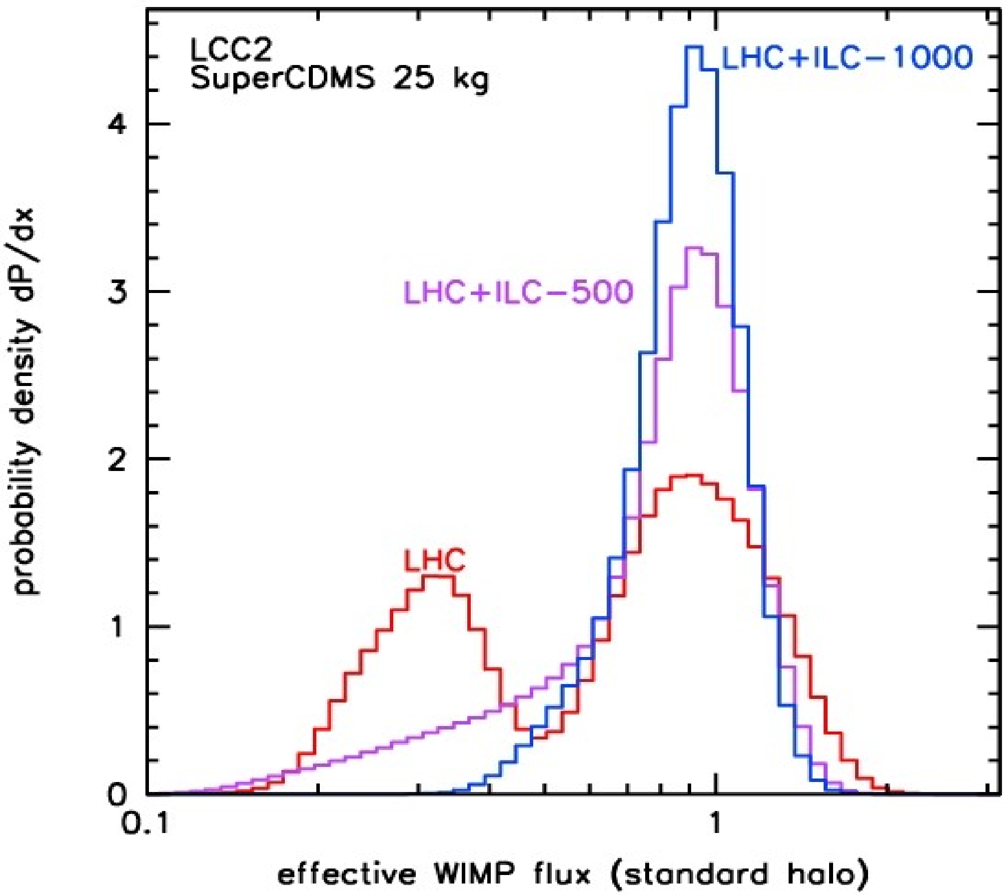
H, A can only be directly discovered at the ILC-1000
direct detection (with ~4 inverse zb) provides strong evidence before this

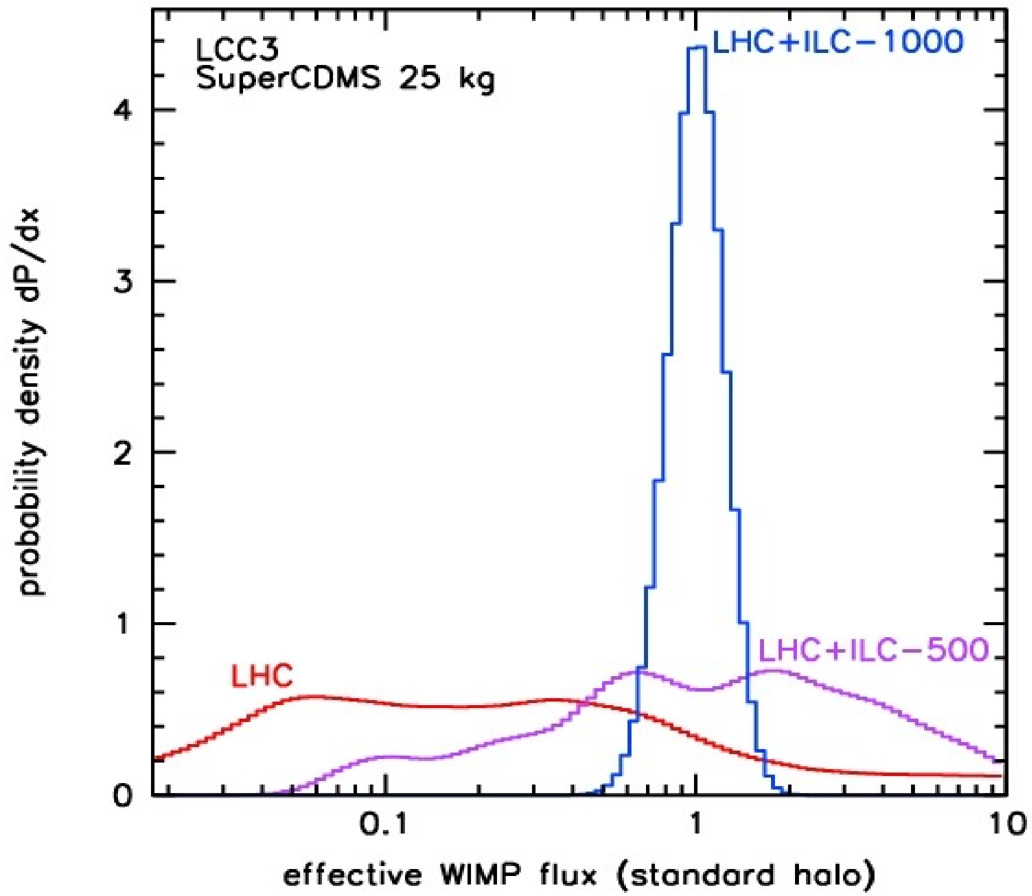
Mapping the Dark Matter in the Galaxy

- Local flux of dark matter particles can be determined from the direct detection rate IF collider data can predict the elastic scattering cross section
- Dark matter density squared along a line of sight can be determined from gamma ray flux IF collider data can predict the annihilation cross section
- These can be done without any astrophysical assumptions

Local Flux of Neutralinos

LCC2 **LCC3**

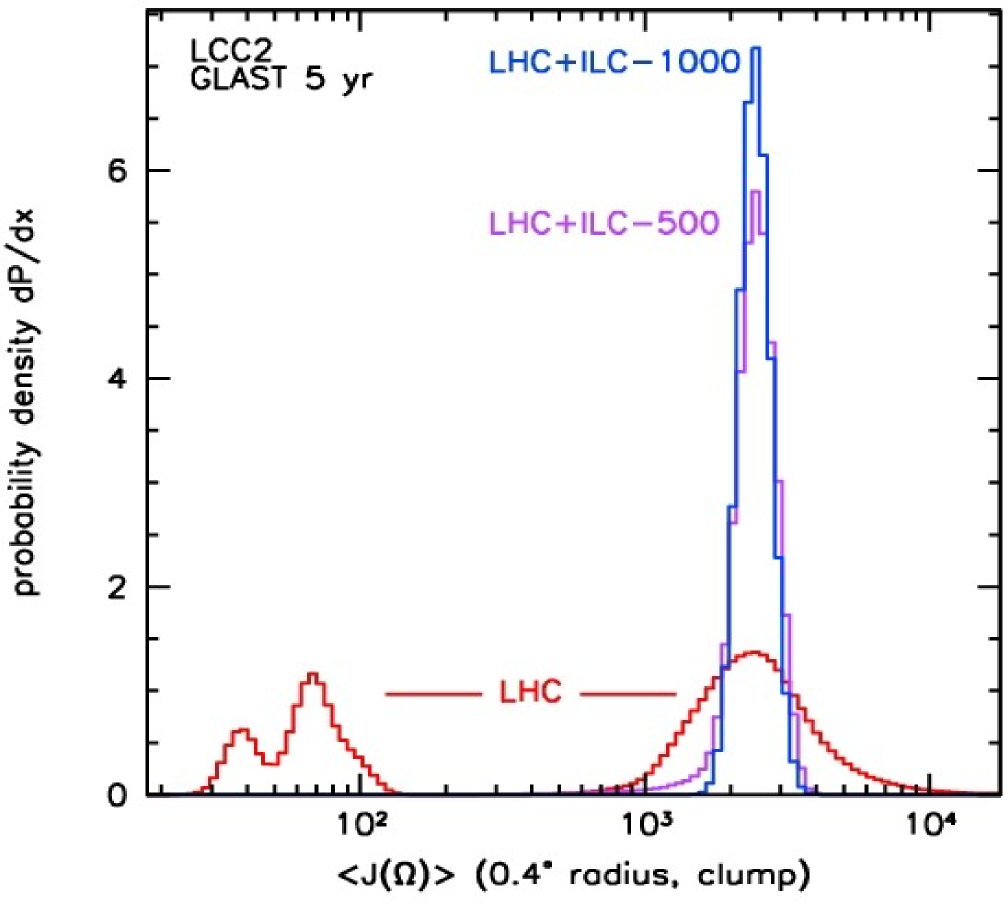


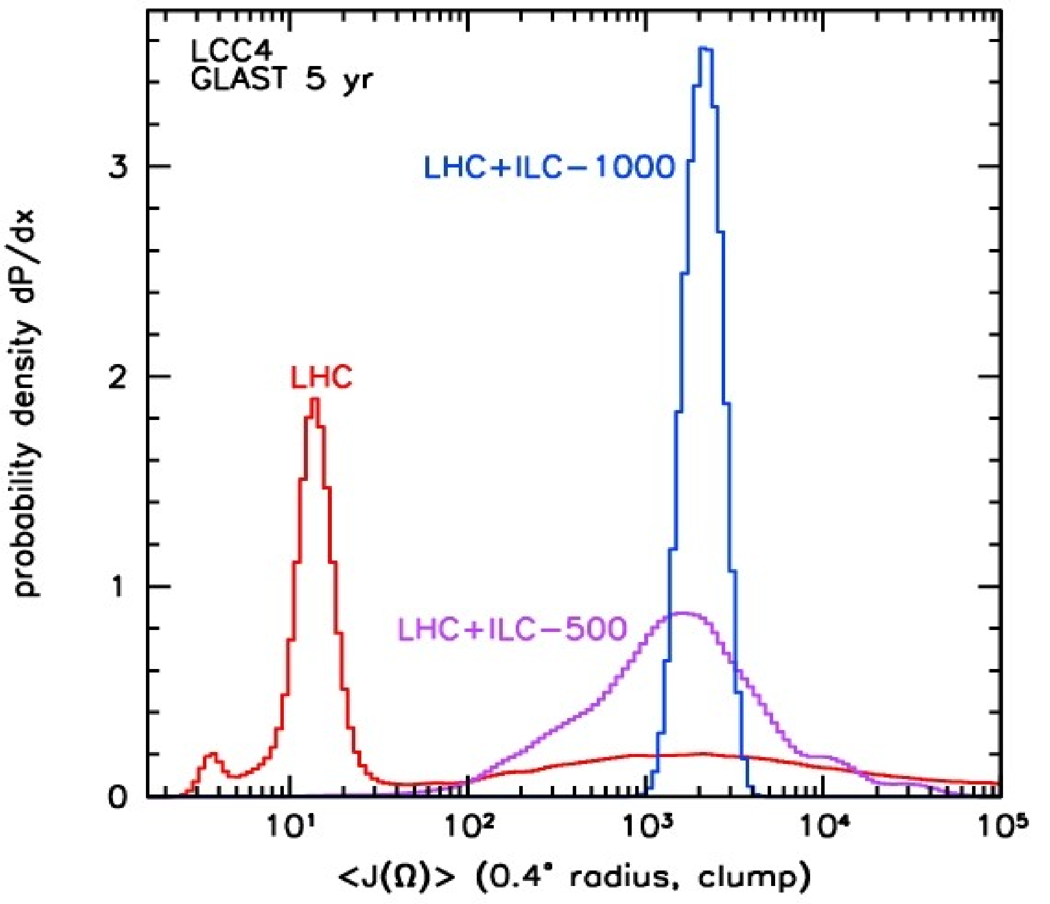


input data: collider + number of counts in direct detection experiment determine WIMP flux with no astrophysical / cosmological assumptions

Dark Matter Annihilation Rate

LCC2 **LCC4**





$$J \propto \int dr\ \rho^2, \qquad N_\gamma \propto J \langle \sigma v \rangle / m^2$$

input data: collider + number of counts in GLAST for one clump
determine J with no astrophysical / cosmological assumptions

Summary

- Solving the dark matter problem requires detecting dark matter in the galaxy, studying its properties in the laboratory, and being able to make the connection between the two

- Experimental approaches are complementary: accelerators, direct detection, indirect detection
  - We need LHC *and* ILC *and* CDMS *and* GLAST
  - Taken together, a consistent picture may emerge

- We can learn about fundamental physics in astrophysical settings, and learn about our galaxy at high-energy colliders